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DIFFERENT TYPES OF VIRAL DISEASES OF PULSE CROPS: SYMPTOMATOLOGY AND THEIR MANAGEMENT

Ankita Bharti^{1*}, Aniket Chandra Rai², Sanjay Yadav¹ and Satwant Yadav³

¹Research Scholar, Department of Plant Pathology,
Acharya Narendra Deva University of Agriculture and Technology, Kumarganj,
Ayodhya, Uttar Pradesh (224229), India.

²Department of Plant Physiology,
Acharya Narendra Deva University of Agriculture and Technology, Kumarganj,
Ayodhya, Uttar Pradesh (224229), India.

³Research Scholar, Department of Mycology and Plant Pathology,
Banaras Hindu University, Banaras, Uttar Pradesh (221005), India.

*Corresponding Email: ankita.bharti8542@gmail.com

Abstract

Plant viruses are a major constraint to pulse production, causing significant quality and yield losses. The virus causes severe disease in many pulse crops, such as Mungbean, Cowpea Mild Mottle Disease (CPMMV), Cowpea Aphid Borne Mosaic Disease, Chickpea Chlorotic Dwarf Disease (CpADV), etc., and many insect vectors transmit these viral diseases. Infected plants show different types of symptoms, and IDM practices can control these viral diseases in plants.

Keywords: Insect vector, Viral diseases.

Introduction

Pulse crops are important legume crops globally that provide a rich source of protein, vitamins, minerals and essential amino acids and improve soil fertility through biological nitrogen fixation, their production is severely affected by viral diseases. which causes yield and quality losses worldwide, transmitted mainly by insect vectors as well as through infected seeds in some cases. It causes different types of symptoms in infected plants. There are some viral diseases in pulse crops and their management.

Yellow mosaic disease of Mungbean

It is the most destructive disease of mungbean, caused primarily by *begomoviruses* belonging to the family *Geminiviridae*, particularly Mungbean yellow mosaic virus (MYMV) and Mungbean yellow mosaic India virus (MYMIV). It is transmitted by Silverleaf whitefly in a persistent, circulative manner. Yield losses vary from 10%-100%, depending on the stage of infection, vector population, susceptibility and environmental conditions.

The symptoms will occur 7-15 days after infection, forming small yellow, chlorotic or pale spots on young leaves along the veins. After the disease progresses, these chlorotic spots enlarge and collapse to form a bright yellow or green mosaic pattern. After infection, the leaves lose their green colour due to a reduction in chlorophyll and become completely yellow in a severely infected plant. The leaves show puckering, curling or wrinkling symptoms and may be reduced in size, become thinner, and more fragile, and the plant shows stunted growth with shortened internodes, reduced branching and poor canopy development, as well as delayed flowering and pod formation (Ramesh *et al.*, 2017).

Management

This disease is controlled by using integrated disease management. The IDM approach includes the cultivation of resistant varieties, use healthy and certified seeds, timely sowing, field sanitation, infected plants removal, and regular monitoring of whitefly populations, also by vector management through biological (*Beauveria bassiana*, *Lecanicilium lecanii*, *Metarhizium anisopliae*, *Encarsia Formosa*, *Chrysoperla carnea* and *Coccinella sexmaculata*), cultural and chemical control (seed treatment with Imidacloprid 600 FS and Thiamethoxam 30 FS, Foliar insecticides with Imidacloprid 17.8 SL, Thiamethoxam 25 WG, Acetamiprid 20 SP and Pyriproxyfen 22.9 SC) (Sharma *et al.*, 2016).

Cowpea Mild Mottle Disease (CPMMV)

The *Cowpea mild mottle virus* causes this disease; it is a member of the genus *Carlavirus* (family *Betaflexiviridae*) and is transmitted by Whitefly. This disease affects several pulse crops, such as mungbean, urdbean and soybean. The infected plants primarily develop mild chlorosis and mosaic pattern on young leaves, followed by puckering, curling, stunted growth, delayed flowering and pod formation, and shrivelled seeds. The virus enters the plant after whitefly feeding, then replicates inside the plant cells. The virus affects the chloroplast and reduces chlorophyll content and photosynthesis, and disrupts nutrient transport and plant hormone balance (Navas-Castillo *et al.*, 2011).

Management

If the plant is infected with Cowpea mild mottle virus, then removed. The virus-free seed, resistant varieties, timely sowing, crop rotation, balanced nutrition and field sanitation should be used for management. Regular monitoring of whitefly and control by using yellow sticky traps, conservation of natural enemies (*Beauveria bassiana*, *Lecanicilium lecanii*, *Metarhizium anisopliae*, *Encarsia Formosa*, and *Coccinella sexmaculata*), neem products (Azadirachtin 0.03%, Azadirachtin 0.15%, Neem seed kernel extract, etc.) and selective insecticides (Imidacloprid, Thiamethoxam, Acetamiprid and Diafenthiuron, etc), which reduce the virus transmission (Horowitz *et al.*, 2020).

Cowpea Aphid Borne Mosaic Disease

This disease is caused by the *Cowpea Aphid Borne Mosaic virus*, which is a member of the genus *Potyvirus* (family *Potyviridae*). It primarily infects cowpea but also affects other pulse crops such as urdbean, mungbean and common bean, transmitted by aphid, mainly *Aphis craccivora*, *Aphis gossypii* and *Myzus persicae*, in a non-persistent manner, and can also be transmitted by seeds. The infected plants develop light green mosaic and mottling on young leaves, followed by vein clearing, crinkling, puckering, curling, stunting, delayed flowering, shrivelled and poor pod formation. Infection causes chlorophyll synthesis reduction and a disruption.

Management of Cowpea Aphid-Borne Mosaic Disease will be the same as for Cowpea Mild Mottle Disease (Worrall *et al.*, 2015).

Chickpea Chlorotic Dwarf Disease (CpADV)

It is caused by *Chickpea Chlorotic Dwarf virus*, a member of the genus *Mastrevirus* in the family of *Geminiviridae*, transmitted by Leafhopper (*Orosius albicinctus*), in a persistent, circulative manner. The infected chickpea plants show chlorosis, reduced leaf size, shortened internodes, severe stunting, delayed flowering, poor pod formation and shrivelled seed formation, leading to high yield losses.

Management

There is no cure once plants become infected with this virus. Effective management includes using of healthy and disease-free, resistant seeds, crop rotation, field sanitation, regularly monitoring of leafhoppers, and vector management by using yellow sticky traps, natural enemies (*Beauveria bassiana*, *Lecanicilium lecanii*, *Metarhizium anisopliae*), neem-based products, and some chemicals such as imidacloprid, thiamethoxam, acetamiprid, dinotefuran, and flonicamid helps in the reduction of virus transmission (Zerbini *et al.*, 2017).

Groundnut Bud Necrosis Disease (GBNV)

The disease is caused by *Groundnut Bud Necrosis Virus*, an *orthospovirus* belonging to the family *Tospoviridae*, which infects several pulse crops, including mungbean, urdbean and cowpea, transmitted by Thrips, mainly *Thrips palmi*, *Scirtothrips dorsalis* and *Frankliniella schultzi*, in a persistent propagative manner. It causes chlorotic or necrotic spots, mosaic and ring spots on young leaves of the plant, and also induces necrosis of terminal buds, leaf distortion, stem necrosis, severe stunting, delayed flowering, poor pod formation and shrivelled seeds. After transmission by thrips, the virus enters the plant cell, replicates in the cytoplasm and spreads systemically by the vascular tissues. It damages chloroplasts, reduces chlorophyll synthesis and photosynthesis, and disrupts plant hormones and interferes with nutrient transport. Disease severity increases under warm and dry conditions (Mandal *et al.*, 2001).

Management

It requires an Integrated Disease Management approach because there is no cure once plants are infected with this virus; it includes the use of healthy and virus-free seed, resistant cultivars, field sanitation. For management, apply regular monitoring of thrips and control vectors through blue or yellow sticky traps, use of natural enemies (*Beauveria bassiana*, *Lecanicilium lecanii*, *Metarhizium anisopliae*), neem-based products, and chemicals such as imidacloprid, thiamethoxam, fipronil, spinosad, cyantraniliprole, and chlorantraniliprole, which help reduce virus transmission (Horowitz *et al.*, 2020).

Conclusion

In this case study, conclude that most of the all viral disease of pulses causes severe loss in yield and quality of crops, and are transmitted by many insect vectors, so the control measure of viral disease is to control the transmission by using insecticides, etc. and also by crop rotation, resistant varieties or removal of infected plant parts. The purpose of this study is to know the general information about viral diseases and insect vectors for their control. Future research should be focus on rapid disease diagnostics, virus characterisation, durable host resistance, and climate-resilient disease management to enhance the productivity of pulse crops.

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IMPROVING FARMERS' PRACTICES THROUGH MIXED-LEVEL FACTORIAL EXPERIMENTS

Archana A^{1,2*}, Sukanta Dash², Anil Kumar³ and Vankudoth Kumar^{1,2}

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi-110012, India

²ICAR-Indian Agricultural Statistics Research Institute, Pusa, New Delhi-110012, India

³Krishi Bhavan, Indian Council of Agricultural Research, New Delhi-110001, India

*Corresponding Email: archanamscagri19@gmail.com

Abstract

Farm recommendations are often developed one input at a time, although farmers manage variety, fertilizer, irrigation and crop geometry together. Mixed-level factorial experiments allow researchers to examine such practices simultaneously, even when the factors require different numbers of levels. Using a maize example with two hybrids, three nitrogen doses and four irrigation regimes, this article explains how 24 treatment combinations can be arranged in incomplete blocks to reduce the influence of field variability. It also shows how the mixedfact R package can generate and assess candidate layouts. The approach helps researchers identify useful interactions, compare yield and resource-use responses, and develop recommendations suited to specific production conditions. Sound randomization, careful field implementation and multi-location validation remain essential before the findings are communicated to farmers.

Keywords: Mixed-level factorial, Blocking, Farm recommendations, Treatment interaction, R package mixedfact

Introduction

Farmers make several management decisions at the same time. The performance of a crop variety may depend on the fertilizer dose, irrigation schedule, plant population and other practices used with it. When each practice is studied in a separate experiment, researchers may overlook these joint responses and may recommend an input rate that performs well only under a limited set of conditions.

Mixed-level factorial experiments provide a practical way to study management packages. They evaluate several factors together while allowing each factor to have the number of levels that is agronomically meaningful. The approach is especially useful when the goal is to identify combinations suited to different production environments rather than to announce one average recommendation for every farm.

Why test farm practices together?

Consider a maize trial involving two hybrids, three nitrogen doses and four irrigation regimes. A factorial experiment evaluates every hybrid-nitrogen-irrigation combination. Researchers can therefore estimate the average response to each factor and also examine interactions. For example, a higher nitrogen dose may be useful under adequate irrigation but may provide little benefit when water is severely limited. Such an interaction is more informative for farm decisions than the average nitrogen response alone.

The factorial principle has a long history in agricultural experimentation (Yates 1937). Modern algorithms extend this principle to mixed-level situations and help researchers search for useful arrangements when the numbers of levels differ among factors (Gromping and Fontana 2019).

Understanding the mixed-level structure

The term mixed-level means that the factors do not all have the same number of treatment levels. In the maize example, the treatment structure is shown in Table 1. Multiplying the levels gives $2 \times 3 \times 4 = 24$ treatment combinations. This number may be manageable for a research station, but placing all 24 plots in one block can expose treatment comparisons to large soil and moisture differences.

Table 1. Treatment structure for the illustrative maize experiment

Factor	Number of levels	Treatment levels
Hybrid (H)	2	H1 and H2
Nitrogen dose (N)	3	80, 120 and 160 kg N per ha
Irrigation regime (I)	4	50%, 70%, 85% and 100% of crop-water requirement

Total treatment combinations = $2 \times 3 \times 4 = 24$

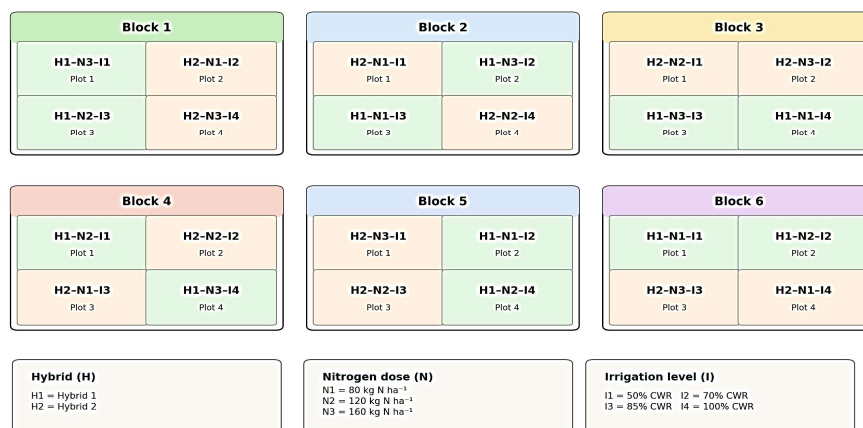
Why incomplete blocks improve field comparisons

Agricultural fields are rarely uniform. Fertility, slope, drainage, soil depth and previous management may change over short distances. Blocking groups nearby and relatively similar plots so that treatment comparisons are less affected by this background variation.

When a complete set of 24 treatments is too large for one uniform block, the trial can use incomplete blocks. In the illustration, six blocks contain four plots each. A block of four plots is easier to keep internally uniform and can also match irrigation channels or machinery movement. Figure 1 shows an illustrative arrangement in which both hybrids and all four irrigation levels occur within every block, while nitrogen levels are distributed across the complete trial. The final field layout must still be generated, checked and randomized before sowing.

Illustrative field layout: $2 \times 3 \times 4$ maize experiment

Six incomplete blocks $\times$ four plots = 24 treatment combinations



CWR = crop-water requirement. The allocation is illustrative; the final field layout should be generated and checked with the selected design method.

Figure 1. Illustrative incomplete-block layout for the $2 \times 3 \times 4$ maize experiment. Source: author-generated illustration.

What can the experiment reveal?

- whether one maize hybrid performs consistently across water regimes;
- whether the yield response to nitrogen changes with irrigation level;
- which combination provides a useful balance of yield, input use and production risk; and
- whether recommendations should differ between water-limited and well-irrigated environments.

These questions are answered by considering both main effects and interactions. A large average nitrogen effect does not support a blanket recommendation when the benefit occurs only under adequate irrigation. Interaction results help convert experimental evidence into management advice for specific production conditions.

Using the mixedfact R package

Preparing a mixed-level blocked design manually can be difficult. The mixedfact R package generates the complete treatment set, assigns treatments to equal-sized blocks and reports diagnostics on confounding, connectedness, orthogonal factorial structure and effect-wise efficiency (Archana *et al.*, 2025). A basic call for the maize example is shown below.

```
install.packages("mixedfact")
library(mixedfact)
maize_design <- mixedfact(levels_vec = c(2, 3, 4), block_size = 4)
```

A candidate layout should not be accepted only because it looks visually balanced. Researchers should confirm that the design is connected, examine the efficiencies of the main effects and interactions that matter most, retain the randomization record and check that the layout is physically workable. The study by Dash and Parsad (2024) also demonstrates the importance of efficient blocking for mixed-level factorial situations.

From trial results to farmer guidance

An efficient design is only the beginning. All field operations should be applied uniformly, and observations should cover more than yield. Water use, fertilizer use, cost of cultivation, net return and production risk can help identify combinations that are both productive and practical.

Promising combinations should be validated across seasons, locations or farmers' fields before wide promotion. This step converts a statistical interaction into a clear recommendation, such as selecting a suitable hybrid and nitrogen dose for a particular water regime. Figure 2 summarizes the pathway from defining the field problem to preparing locally relevant guidance.



Figure 2. Pathway from experimental design to locally relevant farmer guidance.

Source: author-generated illustration.

Practical checklist before laying out the trial

- Choose realistic factor levels and identify priority main effects and interactions before generating the design.
- Select a block size that suits field variability, irrigation, machinery movement, border rows and harvesting.
- Randomize plots within blocks and preserve the final field map and treatment record.
- Record yield together with water use, input use, production cost and relevant risk indicators.
- Validate promising combinations before preparing extension messages or farmer recommendations.

Conclusion

Mixed-level factorial experiments bring agricultural research closer to real farm decision-making because they evaluate several practices together at appropriate numbers of levels. Incomplete blocking makes a large treatment set easier to manage and reduces the influence of field variability. Computational tools such as mixedfact can speed up design generation and provide useful checks, but software cannot replace agronomic judgement, proper randomization and careful field execution. When yield, resource use, cost and risk are considered together and promising results are validated across environments, the experiment can support targeted recommendations instead of a single package for every farmer and field.

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HARNESSING GULKAND: PRODUCTION AND MARKETING TRENDS FOR EMPLOYABILITY AND EXPORT

Arkendu Ghosh^{1*}, Koyel Dey², Manas Mandal³, Rechal Tigga⁴, Madhu Kumari⁴, Soniya Munduiya⁴, Chandan Kumar⁴, Prince⁴, Rahul Ranjan⁴, Thomas Kandeyang⁴, Arun Kumar Singh⁵

¹Assistant Professor Cum Junior Scientist, Department of Fruit Science,
Birsa Agricultural University, West Singhbhum, Jharkhand, India

²Assistant Professor Cum Junior Scientist, Department of Post Harvest Technology,
Birsa Agricultural University, West Singhbhum, Jharkhand, India

³Assistant Professor Cum Junior Scientist,
Department of Floriculture and Landscape Architecture, Birsa Agricultural University,
West Singhbhum, Jharkhand, India

⁴UG Student, Horticulture College, Birsa Agricultural University,
West Singhbhum, Jharkhand, India

⁵Associate Dean, Horticulture College, Birsa Agricultural University,
West Singhbhum, Jharkhand, India

*Corresponding Email: arkofruits@gmail.com

Introduction

Gulkand, a traditional sweet preserve of rose petals, is transitioning from a staple in Ayurvedic apothecaries and local *paan* shops (Figure 1) to a highly lucrative global commodity. India dominates the international trade landscape, commanding nearly 77% of global exports. This surging demand offers dual benefits: it serves as a powerful engine for rural employability and provides an attractive, high-margin avenue for agro-processing exports.

Production Economics and Rural Employability

The production of Gulkand relies on the layered sun-curing of fresh rose petals-traditionally *Rosa damascena* (Damask Rose) or *Rosa centifolia* with sugar. This labor-intensive process provides substantial opportunities for local employment.

Micro-Enterprise Viability

Establishing a small-scale processing unit capable of handling 100 kg of Gulkand per day creates stable, year-round employment. It acts as an excellent micro-enterprise for rural youth and women's self-help groups (SHGs).

Mitigating Crop Volatility

Fresh roses are highly perishable, and raw flower prices fluctuate wildly based on wedding seasons and festival demands. Processing surplus flowers into Gulkand extends shelf-life to over a year. This shields farmers from market crashes and ensures a steady income.

Margin Multiplication

While raw roses yield slim margins, transforming them into Gulkand multiplies the value of the harvest. Processed rose products fetch 3× to 5× higher profit margins compared to selling loose flowers in wholesale mandis.

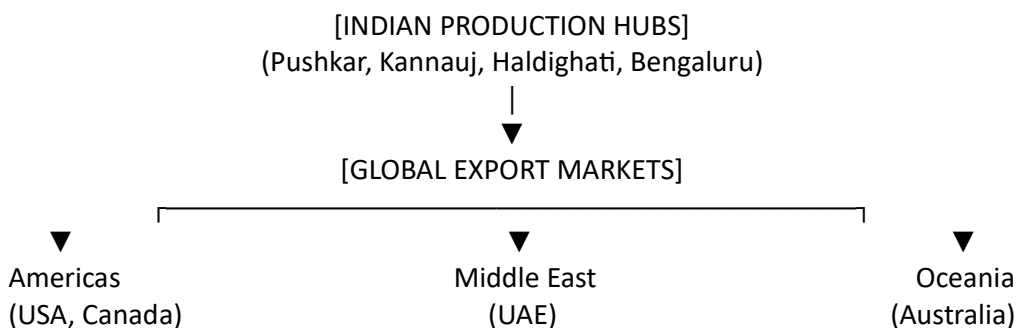
Emerging Marketing and Product Trends

Consumer preferences are shifting toward functional foods, driving innovation in Gulkand formulation and branding.

- **Health-Conscious Formulations:** The modern consumer seeks alternatives to refined white sugar. Producers are capturing premium segments by using organic honey, rock sugar (*mishri*), palm jaggery, and stevia as sweeteners.
- **Gourmet Cross-Pollination:** Gulkand is breaking out of traditional categories. It is now a sought-after ingredient in artisanal fusion foods, including Gulkand-infused chocolates, premium ice creams, and luxury bakery fillings.
- **The D2C Revolution:** Direct-to-Consumer (D2C) e-commerce platforms have leveled the playing field. Small-batch, organic, and single-origin (e.g., "Pushkar Rose Gulkand") brands now bypass exploitative middlemen to sell directly to urban consumers at premium price points.

The Export Landscape

The global market for Gulkand is expanding rapidly, fueled by the Indian diaspora and a growing international appreciation for Ayurvedic wellness products.



Key Export Destinations

The primary markets for Indian Gulkand include the United States, Canada, the United Arab Emirates, Australia, and Kenya. These regions present consistent, high-volume buying potential.

Functional Food Appeal

Beyond traditional culinary uses, international buyers value Gulkand for its therapeutic, cooling properties. Marketing the product as a natural antioxidant, digestive aid, and stress-reliever positions it effectively in western organic food aisles.

Operational Roadblocks and Compliance

Scaling from a domestic backyard setup to an international trading operation requires strict adherence to global food safety standards.

- Cold Chain Logistics:** While cured Gulkand is shelf-stable, international shipping requires controlled environments. This prevents enzymatic browning and maintains the vibrant aroma and texture over long transit times.
- Strict Certification Standards:** European and American markets require comprehensive compliance. Producers must secure FSSAI licensing in India, followed by international certifications such as USDA Organic, ISO 22000, and Halal/Kosher approvals depending on the destination.
- Export Formalities:** Aspiring exporters must register for an Import Export Code (IEC) with the Directorate General of Foreign Trade (DGFT) and enroll with APEDA (Agricultural and Processed Food Products Export Development Authority) to access export incentives and navigate phytosanitary inspections.

Conclusion

Gulkand represents a unique fusion of traditional knowledge, nutritional wellness, and entrepreneurial opportunity, making it a promising value-added product for the floriculture and food processing sectors. Scientific production practices, use of high-quality fragrant rose petals, hygienic processing, attractive packaging, and adherence to FSSAI quality standards can significantly improve product quality, consumer acceptance, and shelf life. The growing demand for natural health foods, herbal products, and functional foods in both domestic and international markets offers considerable scope for expanding Gulkand-based enterprises. Strengthening farmer–processor linkages, promoting cultivation of suitable rose varieties, adopting modern processing technologies, and enhancing branding, geographical identity, and digital marketing will further improve market competitiveness and export potential. Support through skill development, value addition, research, and government initiatives can generate sustainable employment, particularly for rural youth, women entrepreneurs, and small-scale industries. Harnessing these opportunities will transform Gulkand into a high-value horticultural product that contributes to income generation, rural development, and the global promotion of India's traditional herbal heritage.

**Figure 1: Gulkand with Paan****Figure 2: Freshly Prepared Gulkand**

INTEGRATED PEST & DISEASE MANAGEMENT IN COCONUT

Arkendu Ghosh^{1*}, Koyel Dey², Prem Kumar Gupta³, Tushar Kumar³,
Aditya Kumar Baitha³, Vishakha Hessa³, Zoya Adil³,
Shruti Priya³, Arun Kumar Singh⁴

¹Assistant Professor Cum Junior Scientist, Department of Fruit Science,
Birsa Agricultural University, Jharkhand, India

²Assistant Professor Cum Junior Scientist,
Department of Post Harvest Technology,
Birsa Agricultural University, Jharkhand, India

³UG Student, ⁴Associate Dean, Horticulture College,
Birsa Agricultural University, West Singhbhum, Jharkhand, India

*Corresponding Email: arkofruits@gmail.com

Introduction

The coconut palm *Cocos nucifera* L. a member of the Aracaceae family, is one of the most important plantation crops in tropical region and is popularly known as the “Kalpavriksha” (tree of life) due to its multiple uses. It holds great cultural, religious and economic significance in India, which is the 2nd largest producer of coconut after Indonesia. However, coconut palms are vulnerable to several pests that reduce yield and quality. Therefore, integrated pest & disease management (IPDM) is adopted to manage pests through a combination of cultural, biological, mechanical and need-based chemical methods. IPDM ensures sustainable coconut production by reducing pesticide use, protecting the environment, conserving beneficial organisms and improving productivity.

MAJOR PEST OF COCONUT

Rhinoceros beetle (*Oryctes rhinoceros* L.)

This beetle bores into the crown of the palm to feed on sap, damaging the growing tip and unfolding fronds, which often show characteristic V shaped cuts. Severe or repeated attacks can kill young palms and create entry points for secondary infections such as red palm weevil.

Control: The bore hole has to be filled with a mixture of mancozeb and sand @3g/1kg to control this beetle.

Red palm weevil (*Rhynchophorus ferrugineus*)

Considered one of the most destructive coconut pest, the larvae tunnel inside the trunk, feeding internally and causing structural weakening. Infestation is often undetected until significant internal damage has occurring, making early detection critical. This pests affects the palms particularly during the early periods of growth below 20 yrs. Fermenting smell emanating from the injured portions of the palm attract the weevils for egg laying.

Black headed caterpillar (*Opisina arenosella*)

Larvae feed on the underside of leaflets, skeletonizing the leaves and giving palms a scorched appearance. Heavy infestations significantly reduce photosynthetic capacity and nut yield. It is most dominant caterpillar pests of coconut palm. Cutting and burning the infested and fully dried outermost 2-3 leaves removes the pupae and other pest stages in case of severe infestation.



Fig.1. Rhinoceros beetle



Fig. 2. Red palm weevil

MAJOR DISEASES OF COCONUT**Bud rot (*Phytophthora palmivora*)**

A fungal disease that attacks the growing point, causing rotting of the unopened spear leaf and emitting a foul odor. If untreated, bud rot can kill the entire palm within weeks. Give prophylactic spray with 1% Bordeaux mixture. Remove and burn badly affected trees which are beyond recovery.

Stem bleeding (*Thielaviopsis paradoxa*)

This fungal disease causes reddish-brown fluid to ooze from cracks in the trunk, indicating internal tissue decay that weakens the structural integrity of the palms over time.

Controls – root feeding or stem injection technique is followed & maintain the gardens properly with adequate fertilization.

Root wilt disease (kerala wilt)

A phytoplasma-associated disorder causing yellowing of leaves, reduced nut size & gradual decline in productivity, particularly problematic in parts of south asia.

Control – Spray the leaves with 0.01% monocrotophos & apply balanced dose of fertilizers.

Pencil point disease

Because of micronutrient deficiency, the stem will taper towards its tip with lesser number of leaves. The leaf size will be greatly reduced & the leaves will be pale & yellow in colour.

Control- Apply 1% Bordeaux mixture with RDF and poured in the basin of 1.5 radius.



Fig.1. Bud rot



Fig.2. Root wilt

Components of IPDM**Monitoring & early detection**

Regular field scouting is the foundation of IPDM. Farmers & extension workers should inspect crowns, leaf axils & nuts periodically for early symptoms such as boring holes, gum exudation or leaf discoloration. Pheromone traps for Rhinoceros beetle and Red palm weevil greatly improve early detection and allow timely intervention before population build up.

Chemical control (Judicious use)

Chemical intervention should be last resort, applied only when pest or disease pressure exceeds economic thresholds. Root feeding or trunk injection methods are preferred over foliar spraying, as they reduced non-target exposure systemic insecticides may be used selectively for Red palm weevil management when infestation is confirmed.

Mechanical and physical control

Using a barbed hook to physically remove rhinoceros beetles from the crown, placing nylon mesh over the crown of young palms prevents beetle entry into growing point and mass trapping using species-specific pheromone lures reduce adult beetle & weevil population.

Biological control

The fungus *Metarhizium anisopliae* & the baculovirus *Oryctes rhinoceros nudirius* (ORNV) are effective biological agents against rhinoceros beetle population. Avoiding broad-spectrum insecticide use preserves populations of natural enemies & already present in the ecosystem.

Conclusion

Integrated pest & disease management offers coconut growers a practical, economically sound environmentally responsible framework for protecting palm health & securing long-term productivity. By combining vigilant monitoring, sound cultural practices, biological control, targeted mechanical interventions & minimal well-timed chemical use, farmers can manage pest & disease pressure effectively while preserving the ecological balance that sustains coconut farming systems for generation to come. IPDM technologies provide sustainable & profitable income & reduces carbon footprint as well restoring ecosystem vitality & ecological integrity through climate-smart farming is the need of the hour.

AEROPONICS AS A NEXT-GENERATION SOILLESS CULTIVATION SYSTEM FOR RESOURCE-EFFICIENT AGRICULTURE

Jarapla Prashanth*, K.V Ramana Rao and Yogesh A Rajwade

ICAR – Central Institute of Agricultural Engineering, Bhopal

*Corresponding Email: prashanthjarapla17@gmail.com

Abstract

Aeroponics is an advanced soilless cultivation technology in which plant roots are suspended in air and supplied with a nutrient-rich mist. The system can reduce water consumption by 95–98% and increase crop productivity by 20–30% compared with conventional soil-based cultivation. Enhanced root aeration and precise nutrient delivery improve nutrient-use efficiency, plant growth, and crop quality while minimizing fertilizer losses. The technology is particularly suitable for controlled-environment and vertical farming systems, where space utilization can be significantly increased. Although challenges such as high initial investment and dependence on continuous system operation remain, recent advances in automation, sensors, and artificial intelligence have improved system reliability and efficiency. Overall, aeroponics represents a sustainable and resource-efficient approach to meeting future food demands under conditions of limited land and water resources.

Introduction

The global agricultural sector is undergoing a period of significant transformation amid mounting challenges posed by population growth, rapid urbanization, diminishing arable land, climate variability, and freshwater scarcity. Conventional soil-based cultivation systems, despite their historical significance in ensuring food security, are increasingly constrained by declining soil fertility, excessive water consumption, environmental degradation, and limited production efficiency. The situation is particularly critical in developing countries such as India, where expanding urban infrastructure and industrial development continue to reduce the availability of cultivable land while simultaneously increasing food demand.

In recent decades, controlled environment agriculture has emerged as a promising solution to address these challenges by efficiently utilizing space, water, nutrients, and energy. Among the various forms of controlled environment agriculture, aeroponics has gained considerable attention for its exceptional resource-use efficiency and potential to support intensive crop production within limited spatial boundaries. Aeroponics is a specialized soilless cultivation technology in which plant roots are suspended in an enclosed chamber and periodically exposed to a nutrient-rich mist, thereby eliminating the need for soil or solid growing media. This cultivation approach creates an environment characterized by high oxygen availability, precise nutrient delivery, and optimized root-zone conditions, all of which contribute to enhanced plant growth and productivity.

The significance of aeroponics has increased substantially as vertical farming systems and urban agriculture initiatives have advanced. Unlike conventional cultivation methods, aeroponic systems can be established in rooftops, balconies, greenhouses, warehouses, and indoor growing facilities, enabling food production independent of soil quality and seasonal limitations. Furthermore, the technology has demonstrated remarkable water-use efficiency, with several studies reporting

water savings of up to 95–98% compared with traditional field cultivation. Such advantages position aeroponics as a viable strategy for sustainable agricultural intensification and future food security.

Concept of Aeroponics

Aeroponics is derived from the Greek words "aer," meaning air, and "ponos," meaning labor or cultivation. The technology operates on the principle that plant growth can be optimized when roots receive unrestricted access to oxygen while simultaneously obtaining precise quantities of water and mineral nutrients. In contrast to conventional soil cultivation, where nutrient movement depends largely on soil moisture dynamics and root exploration, aeroponic systems directly deliver nutrients to the root surface through atomized droplets generated by specialized misting devices.

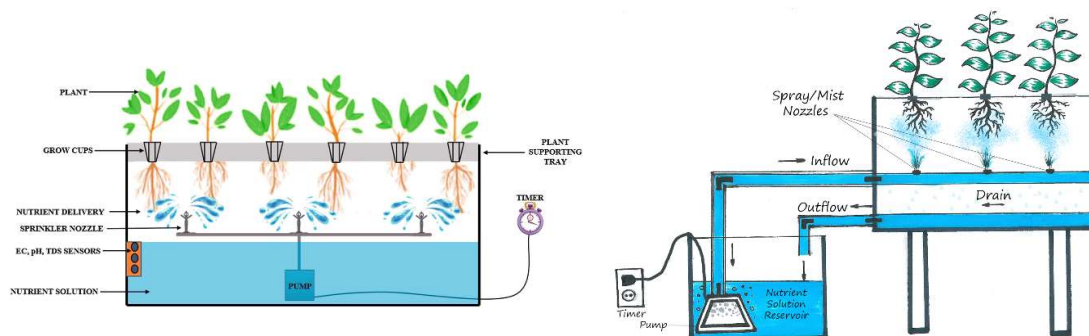


Aeroponics vs. Hydroponics vs. Soil Cultivation

The root environment in an aeroponic chamber differs fundamentally from that in both soil-based and hydroponic cultivation systems. In soil, oxygen diffusion is often restricted by compaction, poor drainage, or excessive moisture. Similarly, in hydroponic systems, roots remain partially or fully submerged in nutrient solution, potentially limiting oxygen availability if aeration is inadequate. Aeroponic systems overcome these limitations by maintaining roots in a highly oxygenated environment while providing intermittent nutrient application through fine droplets. This unique combination promotes accelerated root respiration, enhanced nutrient uptake efficiency, improved metabolic activity, and greater biomass accumulation.

Components of an Aeroponic System

An aeroponic cultivation system consists of several integrated components designed to ensure precise nutrient delivery and environmental regulation. The nutrient reservoir serves as the storage unit for water and dissolved mineral nutrients required for plant growth. A pump transfers nutrient solution from the reservoir to a network of misting nozzles strategically positioned within the root chamber. These nozzles atomize the nutrient solution into fine droplets and distribute them uniformly across the suspended root system. The root chamber is designed to exclude light, preventing algal growth while maintaining optimal humidity around the roots. Automated controllers and timers regulate misting frequency and duration.



Misting System

The effectiveness of aeroponic cultivation is strongly influenced by droplet size, nutrient concentration, oxygen availability, and environmental control. These parameters are greatly influenced by nozzle type, operating pressure, and nozzle installation height from the rootzone. Many studies indicate that mist droplet sizes should range from 30 to 100 μm to provide optimal root wetting while maintaining sufficient oxygen exposure. Droplets smaller than 30 micrometers may remain suspended as fog and fail to adequately hydrate root tissues, whereas droplets larger than 100 micrometers can reduce oxygen diffusion by excessively saturating the root surface. Consequently, precise control of mist generation represents one of the most critical factors governing system performance. Under standard operating conditions, the nutrient solution is sprayed for 30 seconds every 5 minutes throughout the day. This cyclic application ensures continuous nutrient availability while preventing root desiccation.



Nutrient Supplements

The plant requires 16 essential nutrients, of which Carbon, Hydrogen, and oxygen are available naturally, and silicon has a negligible effect. So nutrient solutions typically contain other essential macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, as well as micronutrients including iron, zinc, manganese, boron, copper, and molybdenum. The optimal nutrient concentrations recommended by various scientists are presented in Table 1. To prevent nutrient precipitation and ensure stability, concentrated stock solutions are commonly prepared as two separate solutions, designated Solution A and Solution B. Solution A typically contains calcium nitrate, potassium nitrate, and an iron chelate, while Solution B contains monopotassium phosphate, magnesium sulfate, and all the micronutrients. For example, a 5 L stock solution may be prepared by dissolving the required amounts of fertilizers separately in 5 L of distilled water. During operation, measured volumes of Solutions A and B are diluted with water in the nutrient reservoir to achieve the desired nutrient concentration and electrical conductivity (EC) suitable for

crop growth. Monitoring devices, such as pH and electrical conductivity sensors, are essential for maintaining nutrient solution quality and ensuring nutrient availability remains within acceptable limits for crop growth. Recommended pH values generally range between 5.5 and 6.5, while electrical conductivity values typically range from 1.5 to 2.5 dS m⁻¹ depending on crop requirements.

Table 1. Concentration of Essential Mineral Elements in Different Nutrient Solutions Used in Aeroponic Systems (mg L⁻¹)

Nutrient (mg L ⁻¹)	Nutrient	Steiner (1984)	Cooper (1988)	Hewitt (1966)	Hoagland and Arnon (1938)
Nitrogen	N	168	200–236	168	210
Phosphorus	P	31	60	41	31
Potassium	K	273	300	156	234
Calcium	Ca	180	170–185	160	160
Magnesium	Mg	48	50	36	34
Sulfur	S	336	68	48	64
Iron	Fe	2–4	12	2.8	2.5
Copper	Cu	0.02	0.1	0.064	0.02
Zinc	Zn	0.11	0.1	0.065	0.05
Manganese	Mn	0.62	2	0.54	0.5
Boron	B	0.44	0.3	0.54	0.5
Molybdenum	Mo	Not considered	0.2	0.04	0.01

Optimal Microclimatic Conditions

Microclimatic conditions play a crucial role in the performance of aeroponic systems. Temperature and relative humidity must be maintained within optimal ranges to ensure efficient nutrient uptake, root development, and plant growth. In any leafy veggie's cultivation, the air temperature is generally maintained between 22–28°C during the day and 18–22°C at night, while the root-zone temperature is kept between 20–24°C. Relative humidity is typically maintained at 60–80% to minimize plant water stress and prevent excessive transpiration. Environmental parameters are continuously monitored using temperature and humidity sensors, and regulated through ventilation, cooling, heating, or humidification systems to provide a stable growing environment and maximize crop productivity.

Lighting Conditions

Artificial lighting is an important component of indoor aeroponic systems, providing the energy required for photosynthesis when natural sunlight is insufficient. Full-spectrum LED grow lights are commonly used because they supply wavelengths across the photosynthetically active radiation (PAR) range while maintaining high energy efficiency and low heat generation. Any leafy green cultivation typically maintains a photoperiod of 14–16 hours of light and 8–10 hours of darkness per day to promote vigorous vegetative growth. Light intensity and duration are controlled using automated timers to ensure consistent plant development and maximize biomass production.

Advantages and Limitations

Aeroponics offers several advantages, including efficient use of water and nutrients, faster plant growth, higher yields, improved root aeration, and reduced risk of soil-borne diseases. It also enables year-round cultivation in controlled environments with minimal land requirements.

However, the system has certain limitations, such as high initial installation costs, dependence on electricity and automated equipment, the need for continuous monitoring, and the risk of rapid plant stress or crop loss if the misting system fails. Despite these challenges, aeroponics remains a promising technology for sustainable and resource-efficient crop production.

Need for Aeroponic Cultivation in Modern Agriculture

The growing importance of aeroponic technology is driven by increasing food demand, limited agricultural land, water scarcity, and climate-related challenges. Aeroponics addresses these issues by producing high crop yields while using significantly less water and land than conventional farming. Its recirculating nutrient delivery system can reduce water consumption by up to 95–98%, making it suitable for water-limited regions. Additionally, aeroponics supports vertical and urban farming, enabling efficient food production in limited spaces and contributing to sustainable and localized food security.

Conclusions

Aeroponics is an advanced, sustainable cultivation technology that offers a highly efficient alternative to conventional soil-based agriculture. By delivering water and nutrients directly to plant roots as a fine mist, the system maximizes resource-use efficiency while promoting rapid growth, higher yields, and improved crop quality. Its ability to significantly reduce water consumption, minimize nutrient losses, and enable cultivation in limited spaces makes it particularly valuable in addressing contemporary challenges such as water scarcity, land degradation, urbanization, and climate change. Although high initial investment costs and dependence on reliable system management remain important constraints, ongoing advancements in automation, sensors, artificial intelligence, and controlled-environment agriculture are improving the feasibility and scalability of aeroponic systems. As global demand for food continues to rise, aeroponics has the potential to play a vital role in future sustainable agricultural production, contributing to enhanced food security and efficient resource conservation.

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**EL NINO, CLIMATE CHANGE AND GLOBAL UNCERTAINTIES:
IMPLICATIONS FOR INDIAN AGRICULTURE AND FUTURE RESILIENCE****K. N. Tiwari**

Ex Director, International Plant Nutrition Institute, India Program, 4/861,
Hanumat Kripa, Gomti Nagar Extension, Lucknow 226010

*Corresponding Email: kashinathtiwari730@gmail.com

Abstract

Indian agriculture, which supports the livelihoods of a large population, is highly sensitive to climatic and global disruptions. This paper examines the impacts of El Niño, climate change, and emerging global uncertainties on Indian agriculture and explores strategies for enhancing resilience. El Niño often alters monsoon patterns, leading to droughts, heat waves, and reduced water availability, which adversely affect crop productivity and farm incomes. Climate change further intensifies these challenges through rising temperatures, erratic rainfall, and increased frequency of extreme weather events. Additionally, global uncertainties such as geopolitical conflicts, supply-chain disruptions, and market volatility influence agricultural input costs and food security. The paper highlights key challenges and impacts while emphasizing climate-smart agriculture, efficient water management, resilient crop varieties, early warning systems, and supportive policies as essential pathways for ensuring sustainable and resilient agricultural development in India.

Introduction

Climate change has emerged as one of the most serious long-term challenges for Indian agriculture. Rising global temperatures, erratic rainfall, frequent droughts and floods, increasing intensity of cyclones, heat waves, and other extreme weather events are affecting agricultural production. The impact of these changes is even more severe in a monsoon-dependent agricultural country like India. Numerous studies by agricultural scientists and international organizations indicate that if current climate trends continue, there could be widespread impacts on agricultural productivity, water availability, and food security.

Among these climate challenges, El Niño is a crucial global climate phenomenon that has a direct impact on the Indian monsoon. El Niño is an ocean-atmospheric phenomenon caused by an abnormal increase in sea surface temperatures in the Pacific Ocean, affecting rainfall and temperature patterns across various regions of the world. A significant relationship has long been observed between the Indian monsoon and El Niño. Historically, El Niño has been implicated in several major drought years in India, such as 1877, 1918, 1972, 1982, 1987, 2002, 2009, and 2015. While not every El Niño year causes drought, the monsoon is more likely to weaken during these years than normal.

A major reason for the vulnerability of Indian agriculture is that a large part of the country's agricultural sector is still rain-fed. Despite the expansion of irrigation facilities, nearly half of the agricultural area remains directly dependent on monsoon rainfall. Therefore, any change in the amount, timing, and distribution of rainfall can impact crop production, farmers' incomes, and the rural economy. Small and marginal farmers, who constitute the majority of total farming

households in India, are particularly vulnerable to climate and monsoon uncertainties because they have limited resources and risk management options.

Current global circumstances further complicate this challenge. The Russia-Ukraine conflict, rising tensions in the Middle East, volatility in global energy markets, disruptions in supply chains, rising fertilizer prices, and uncertainties related to food trade are posing new challenges to the agricultural sector. Rising energy prices impact irrigation, farm mechanization, and transportation costs, while fluctuations in the global availability and prices of fertilizers directly increase agricultural production costs. This can, in turn, impact farmer profitability and the competitiveness of the agricultural sector.

Additionally, concerns about global food security are growing. Climate change and geopolitical crises are impacting agricultural production in many countries, leading to increased instability in international food markets. For a country with a large population like India, food security is not just a matter of production, but also a question of social and economic stability. Therefore, agricultural policymaking requires an integrated approach to production, distribution, price stability, and nutritional security.

Under these circumstances, Indian agriculture faces a dual challenge. It must meet the food needs of a growing population, while simultaneously conserving natural resources and addressing the impacts of climate change. The solution to this challenge lies not simply in expanding traditional agriculture, but in a comprehensive restructuring of the agricultural system. Concepts such as climate-smart agriculture, conservation agriculture, regenerative agriculture, precision agriculture, digital agriculture, and integrated farming systems are becoming important components of future agricultural strategies.

In particular, the integration of regenerative agriculture and climate-smart agriculture can play a key role in making Indian agriculture more resilient. Practices such as soil health improvement, carbon sequestration, water conservation, biodiversity enhancement, and agroforestry not only help mitigate the impacts of climate change but also enhance long-term productivity and profitability. Similarly, the use of digital technologies, artificial intelligence, drones, remote sensing, and weather-based agricultural advisory systems can make agricultural decisions more scientific and effective.

The Indian government has also taken several initiatives in recent years to make the agriculture sector more sustainable and climate-resilient. These include the Pradhan Mantri Krishi Sinchai Yojana, the Soil Health Card Scheme, the promotion of natural farming, the Digital Agriculture Mission, and the Kisan Efforts such as the Farmer Producer Organization (FPO) program and water conservation campaigns are providing new direction to the agricultural sector. However, the success of these initiatives will depend on how effectively they reach farmers and how successfully they are implemented according to local conditions.

In the current scenario, it is clear that the combined impacts of El Niño, climate change, and global uncertainties present a multifaceted challenge for Indian agriculture. This challenge not only concerns agricultural production, but also water security, food security, farmers' incomes, rural development, and national economic stability. Therefore, future agricultural policy must move beyond short-term crisis management and focus on long-term resilience building, resource conservation, and technological innovation. In this context, the present article aims to provide a

comprehensive analysis of the scientific background of El Niño, its relationship to the Indian monsoon, its potential impact on Indian agriculture, the additional challenges posed by current global conditions, and the strategies needed by farmers, policymakers, and agricultural scientists. Furthermore, this paper seeks to identify and recommend practical and science-based strategies for transforming Indian agriculture into a more productive, sustainable, climate-resilient, economically viable, and inclusive sector capable of addressing the challenges posed by El Niño, climate change, and global uncertainties. Thus, this paper not only analyses the current challenges but also presents a long-term and strategic development vision for Indian agriculture.

El Nino Phenomenon and Its Relationship with the Indian Monsoon

El Niño is one of the Earth's most significant natural climate phenomena, whose impact is not limited to the Pacific Ocean region, but also affects rainfall, temperature, agricultural production and water resources in many countries around the world. Indian agriculture, which is primarily dependent on the southwest monsoon, is considered particularly vulnerable to El Niño events (**Fig. 1**). In India, agricultural production, water availability, food security and a large part of the rural economy depend on monsoon rainfall, hence studying El Niño conditions is extremely important for Indian agricultural planning and policy making.

Scientifically, El Niño is the warm phase of the oceanic-atmospheric system called El Niño Southern Oscillation (ENSO). Under normal circumstances, the water in the western part of the equatorial Pacific Ocean (near Indonesia and Australia) remains relatively warm, while the water in the eastern part (near the coasts of Peru and Ecuador) is relatively cold. Due to this temperature difference, the trade winds blow from east to west, and there is an abundance of clouds and rainfall in the western Pacific region.

El Niño occurs when these trade winds weaken or sometimes even temporarily shift direction. As a result, warm water from the western Pacific spreads toward the eastern and central Pacific. This unusual increase in sea surface temperatures affects global atmospheric circulation and alters normal rainfall and temperature patterns in various regions. These changes further impact agriculture and climate in many regions, including Asia, Africa, the Americas, and Australia.

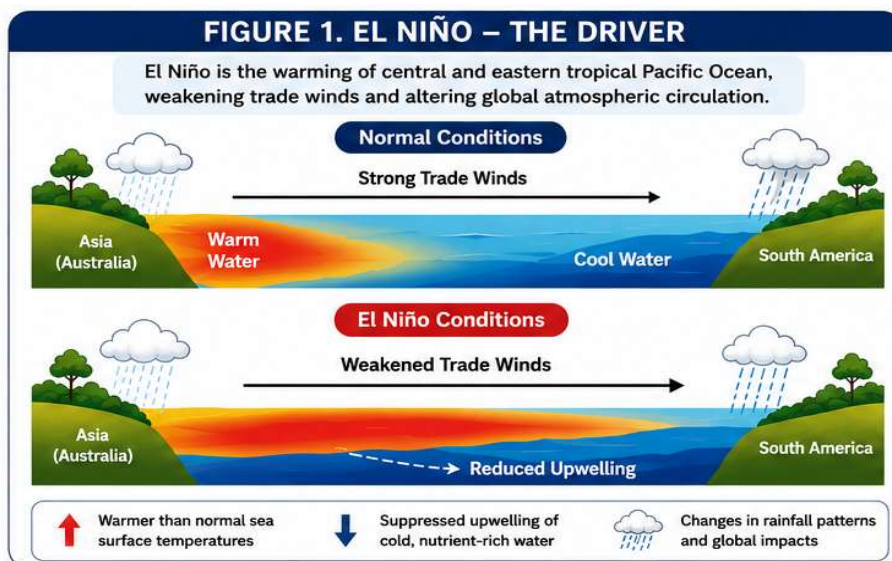


Fig.1 El Nino is the driver of climate change

Scientific background of El Niño: El Niño is a large-scale ocean-atmosphere phenomenon that originates in the tropical Pacific Ocean and influences weather and climate patterns across the globe. It is a key component of the El Niño–Southern Oscillation (ENSO), a naturally occurring climate system characterized by periodic fluctuations in ocean temperatures and atmospheric conditions. El Niño events generally occur every 2 to 7 years and may persist for 9 to 18 months, although their duration and intensity can vary considerably. Depending on the extent of ocean warming, El Niño episodes are classified as weak, moderate, or strong, with stronger events producing more significant climatic impacts.

Scientifically, El Niño is identified by a sustained increase in sea surface temperatures (SSTs) in the central and eastern equatorial Pacific Ocean. When SSTs rise at least 0.5°C above the long-term average for several consecutive months, El Niño conditions are considered to have developed. However, ocean warming alone does not fully explain the phenomenon. Changes in atmospheric pressure patterns, particularly the Southern Oscillation, weakening of the easterly trade winds, alterations in ocean currents, and shifts in cloud formation and rainfall distribution are equally important. These interconnected oceanic and atmospheric processes reinforce one another, creating a complex climate system that affects weather patterns worldwide, including monsoon behaviour, temperature regimes, and precipitation patterns across India.

Mechanism of Indian Monsoon and El Niño: The Indian southwest monsoon is one of the most important climatic systems in the world and serves as the primary source of rainfall for the Indian subcontinent. Its formation is mainly driven by the differential heating of land and sea during the summer months. As temperatures rise, the Indian landmass heats up more rapidly than the surrounding oceans, creating a low-pressure zone over northern and central India. In contrast, the Indian Ocean remains relatively cooler and develops a comparatively high-pressure area. This pressure difference draws moisture-laden winds from the Arabian Sea and the Bay of Bengal toward the Indian subcontinent, resulting in widespread monsoon rainfall.

El Niño significantly influences this monsoon system by altering global atmospheric circulation patterns. During an El Niño event, the warming of the central and eastern equatorial Pacific Ocean weakens the normal east-to-west trade winds and modifies the Walker Circulation, a large-scale atmospheric circulation pattern across the tropics. These changes can reduce the transport of moisture toward South Asia and weaken the monsoon circulation, often leading to below-normal rainfall, delayed monsoon onset, and an increased risk of drought in many parts of India.

However, the relationship between El Niño and the Indian monsoon is complex and not always predictable. Recent scientific studies indicate that several other climatic factors also influence monsoon behaviour, including the Indian Ocean Dipole (IOD), Madden–Julian Oscillation (MJO), Eurasian snow cover, Himalayan cryospheric conditions, and regional sea surface temperatures. A positive IOD, for example, can sometimes offset the adverse effects of El Niño and support normal monsoon rainfall. Consequently, while El Niño remains an important predictor of monsoon variability, its impact depends on interactions with multiple atmospheric and oceanic processes operating simultaneously.

Historical relationship between El Niño and drought in India: Several major droughts in India's agricultural history have been associated with El Niño years. Years such as 1877, 1899, 1918, 1972, 1982, 1987, 2002, 2009, and 2015 experienced El Niño, and in many of these years, the monsoon was weaker than normal. In particular, 1987, 2002, and 2009 are remembered as major drought

years for India. In 2002, a significant reduction in nationwide monsoon rainfall was recorded, affecting agricultural production and leading to a decline in food grain output. Similarly, in 2009, a weak monsoon resulted in drought-like conditions in many states. These events highlighted the extent to which Indian agriculture is dependent on the monsoon and how profoundly global climate events like El Niño can impact the agricultural sector. Although it's important to note that not all El Niño years result in drought, and not all droughts are caused solely by El Niño, a statistically significant correlation has been found between El Niño and weak monsoons.

El Niño and uneven rainfall distribution: El Niño's impact affects not only the total amount of rainfall, but also the spatial and temporal distribution of rainfall. Sometimes, total monsoon rainfall remains near normal, but its distribution is highly uneven. Some areas may experience excessive rainfall, while others may experience prolonged drought. This uneven rainfall makes agricultural management more difficult. Farmers are not only concerned with total rainfall, but also with the timely availability of rainfall at various crop stages. If rainfall is low at sowing time and then excessive later, production can also be affected. Therefore, the uncertainty in rainfall distribution during El Niño further increases agricultural risk.

Temperature rise and increased risk of heat waves: A key characteristic of El Niño years is warmer-than-normal temperatures. Many of the warmest years globally have been associated with El Niño events. In India, the frequency and intensity of heat waves can also increase during El Niño conditions. High temperatures impact crops, livestock, water resources, and human health. High temperatures increase transpiration in crops, increasing water requirements. If rainfall is also low at the same time, crops face double pressure. Wheat, rice, maize, and pulses are particularly sensitive to high temperatures. Additionally, warming temperatures can increase irrigation water demand and lead to greater water losses in reservoirs. Therefore, El Niño poses not only a rainfall challenge but also a heat stress challenge.

Climate change and the changing nature of El Niño: The nature and impacts of El Niño in the context of global climate change are being widely studied within the scientific community. Several studies indicate that rising global temperatures may increase the frequency and impact of intense El Niño events in the future. Although scientific debate is still ongoing, it is clear that the combined effects of climate change and El Niño could pose more serious risks to the agricultural sector. The effects of El Niño, along with rising temperatures, erratic rainfall, and extreme weather events, could make agricultural production more unstable (**Fig.2**). For this reason, in modern agricultural planning, monsoon forecasting alone is not considered sufficient, but continuous monitoring of ENSO, IOD and other global climate indicators is also considered important

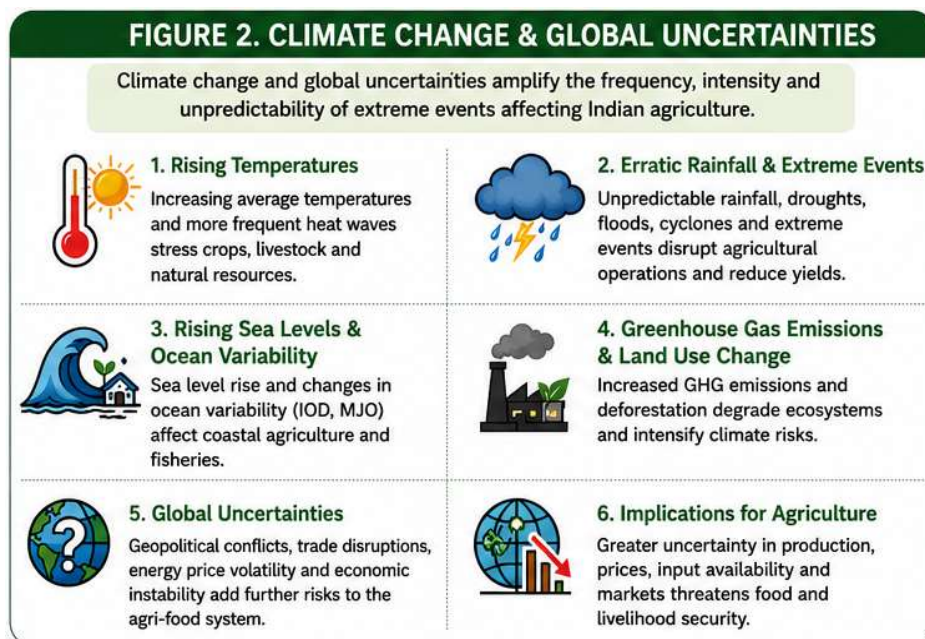


Fig. 2 Climate change and global uncertainties

Relevance of El Niño for Indian agriculture: In India, approximately 50 percent of net sown area still depends on rain-fed agriculture. Many small and marginal farmers in the country cultivate with limited resources and have relatively low risk tolerance. In such a situation, events like El Niño are not just a question of production, but also of farmer income, rural employment, food security, and social stability. Understanding the impacts of El Niño is crucial because it allows governments, scientific institutions, and farmers to make necessary preparations in time. Weather-based agricultural advisories, selection of drought-tolerant varieties, water conservation, crop diversification, and risk management strategies can play a key role in mitigating the potential impacts of El Niño.

Holistic Perspective

El Niño is a complex ocean-atmospheric phenomenon that can have profound impacts on the Indian monsoon and agriculture. It not only causes a reduction in rainfall but also affects rainfall distribution, temperature, water availability, crop productivity, and the agricultural economy. In the current era of climate change, El Niño's relevance has increased as its impacts can be more widespread and complex. Therefore, to ensure the long-term sustainability and food security of Indian agriculture, scientific understanding of El Niño, early forecasting, and effective adaptation strategies must be integrated into agricultural policy and development plans.

Potential impact on Indian agriculture

The impact of El Niño on Indian agriculture is not limited to a reduction in monsoon rainfall; it can affect almost all components of the agricultural ecosystem, natural resources, agricultural economy, and rural livelihoods (**Fig. 3**). India's agricultural system is highly dependent on the monsoon, so changes in the timing, quantity, and distribution of rainfall pose a serious challenge to the sustainability of agricultural production. During El Niño, rainfall deficits, prolonged dry spells, extreme temperatures, pressure on water resources, and rising costs of agricultural inputs combine to create a complex risk landscape. If such a situation is combined with a global energy

crisis, fertilizer supply disruptions, or food market instability, the impacts can be even more widespread. Therefore, a multifaceted analysis of the potential impacts of El Niño on Indian agriculture is essential.

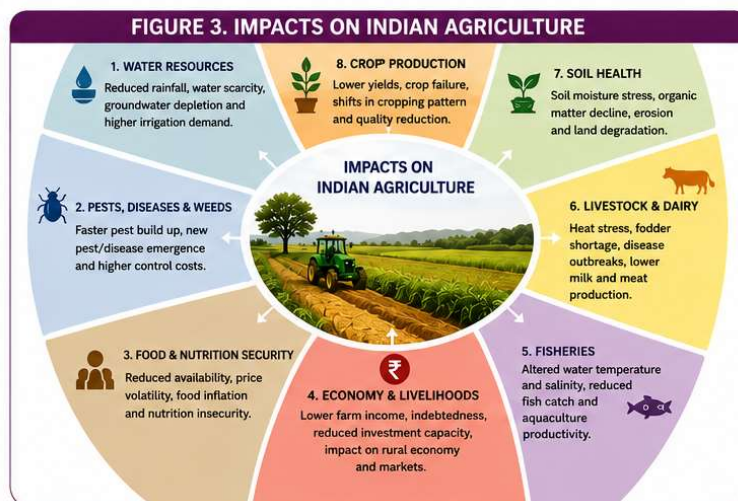


Fig. 3 Impact of El-Niño on Indian Agriculture

Impact on Kharif Crops: The role of Kharif season in Indian agriculture is very important because a major part of the total annual food grain production of the country is obtained in this season. Paddy, maize, millet, sorghum, soybean, cotton, groundnut, pigeon pea and other major Kharif crops are directly dependent on monsoon. In the event of El Nino, if the monsoon arrives late or there is less rainfall than normal, then the sowing area may decrease. In many areas, farmers are not able to sow on time, due to which the growth period of the crop gets reduced and the yield gets adversely affected.

Adequate water availability is crucial in early-stage crops like rice. Lack of rainfall can impact seedling establishment and delay transplanting. Similarly, moisture stress can also reduce yields in cash crops like soybean and cotton. Frequent dry spells during the monsoon season can disrupt flowering, fruit formation, and grain filling processes, resulting in declines in both yield and quality.

Temperature increases are also a significant factor during El Niño. Higher temperatures increase plant respiration, leading to greater use of energy produced by photosynthesis. This impacts biological productivity and can slow crop growth. Numerous scientific studies have shown that persistently high temperatures play a significant role in reducing crop productivity.

Impact on Rabi Crops: The impact of El Niño isn't limited to the Kharif season ; its effects are also clearly visible in Rabi crops. If the monsoon is weak, reservoirs, ponds, and groundwater sources may not store enough water. This directly impacts irrigation systems during the Rabi season. wheat, chickpea, lentils, peas, and mustard require adequate moisture at various stages of growth. If irrigation water availability is limited, farmers may have to reduce crop area or resort to additional irrigation costs. This increases agricultural production costs and reduces profitability. Additionally, recent years have seen unusually high temperatures during the Rabi season. If temperatures remain above normal in February and March, the grain filling process in wheat can

be affected, resulting in smaller grain sizes and lower overall production. Therefore, the effects of El Niño can sometimes persist into the next agricultural season.

Impact on water resources: uses approximately 80 percent of all available freshwater. In such a situation, a weakened monsoon has the most serious impact on water resources. Reduced rainfall during El Niño can cause water levels in rivers, reservoirs, lakes, and ponds to decline. This impacts the efficiency of irrigation projects and increases pressure on agricultural production. In areas with groundwater-based irrigation, farmers exploit groundwater in excess to compensate for the lack of rainfall. This can cause water levels to drop rapidly. States like Punjab, Haryana, Rajasthan, Gujarat, Karnataka, and Tamil Nadu already face groundwater stress, and El Niño conditions could exacerbate this problem. The increasing pressure on water resources is not limited to agriculture. Drinking water, animal husbandry, rural industries, and ecosystems are also affected. Therefore, water management becomes one of the most important challenges in the context of El Niño.

3.4 Impact on soil health and nutrient cycling: Soil health is a cornerstone of agricultural productivity. Drought and heat stress during El Niño can affect the physical, chemical, and biological properties of soil. Lack of moisture reduces the activity of beneficial soil microorganisms, affecting nutrient mineralization and their availability to plants. Persistent drought can cause the soil to harden, restricting root growth. The soil's water-holding capacity decreases, preventing plants from accessing the moisture they need. On the other hand, if a prolonged drought is followed by sudden heavy rainfall, soil erosion and nutrient runoff can increase. Conservation of soil organic carbon and utilization of organic matter become extremely important under El Niño conditions as they help in increasing the water holding capacity of the soil and reducing the impact of drought.

Impact on pest, disease and weed management: El Niño and climate change can significantly influence the occurrence, distribution, and intensity of pests, diseases, and weeds in agricultural systems. Variations in temperature, humidity, and rainfall patterns create favourable conditions for the rapid growth and multiplication of many insect pests and plant pathogens. Higher temperatures often accelerate the life cycles of pests, allowing them to reproduce more quickly and increase their population density within a single cropping season. As climatic conditions change, certain pests and diseases may also expand into new geographical regions where their incidence was previously low or absent.

Moisture-stressed crops are generally weaker and less capable of resisting pest and disease attacks. Consequently, farmers may experience greater crop losses and may need to apply additional pesticides, fungicides, and insecticides to protect their crops. This increases production costs and can create environmental concerns if chemical use becomes excessive. El Niño-related weather conditions can also enhance the growth and competitiveness of weeds, which compete with crops for water, nutrients, sunlight, and space, thereby reducing crop productivity. Furthermore, changing climatic conditions increase the likelihood of the emergence of new pests, diseases, and invasive weed species. These evolving challenges require continuous research, effective surveillance systems, and strengthened agricultural extension services to support farmers in adopting appropriate pest and disease management strategies.

Impact on Animal Husbandry and Dairy Sector: Animal husbandry and dairying are important components of the Indian agricultural economy, providing income, employment, and nutritional

security to millions of rural households. However, El Niño-induced climatic disturbances can significantly affect the livestock sector. Reduced and erratic rainfall during El Niño years often leads to shortages of fodder and drinking water, creating serious challenges for livestock management. Diminished pasture growth and lower availability of green fodder adversely affect animal nutrition, resulting in reduced productivity and poor health.

High temperatures associated with El Niño events further aggravate the situation by increasing heat stress among livestock. Heat-stressed animals consume less feed, experience reduced growth rates, and become more susceptible to diseases and infections. Dairy animals, particularly buffaloes and high-yielding exotic cattle breeds, are highly sensitive to elevated temperatures. As a result, milk production often declines, reproductive efficiency decreases, and fertility-related problems become more common. In severe cases, prolonged heat stress can increase mortality rates among vulnerable animals.

El Niño can also increase the cost of livestock production. Scarcity of fodder and feed leads to higher market prices, raising the expenses incurred by farmers and dairy producers. Consequently, the production and availability of milk, meat, and other animal products may decline, leading to higher consumer prices. Therefore, El Niño poses a significant threat to the sustainability and profitability of India's livestock and dairy sectors, particularly for smallholder farmers who depend heavily on these activities for their livelihoods.

Agricultural Labour, Rural Employment and Social Impact: The impact of El Niño is not limited to production, but also affects rural employment and social structure. If sown area is reduced or crops are affected, employment opportunities for agricultural workers may decline. This reduces rural incomes and increases economic insecurity. In many drought-affected areas, people may migrate to cities in search of alternative employment. This could impact both labor availability and the social structure in rural areas. Small and marginal farmers, landless laborers, and women farmers are particularly vulnerable to such conditions.

Impact on food security, nutritional security and price stability: Food security and nutritional security are closely linked to the stability of agricultural production. El Niño-induced disruptions in rainfall and temperature patterns can significantly affect the production of food grains, pulses, oilseeds, fruits, and vegetables, thereby posing challenges to the availability, accessibility, and affordability of food. When agricultural output declines due to droughts, moisture stress, or crop failures, market supplies become constrained, often resulting in higher food prices and increased food inflation.

Rising food prices disproportionately affect low- and middle-income households, which spend a significant share of their income on food. Reduced production of pulses and oilseeds is particularly concerning because these commodities are major sources of protein, essential fatty acids, and micronutrients for a large segment of the Indian population. Shortages and higher prices can limit consumption, thereby increasing the risk of nutritional deficiencies, especially among vulnerable groups such as children, women, and economically weaker sections.

El Niño can also adversely affect livestock production through fodder and water shortages, reducing the availability of milk, meat, and other animal-based food products. This further weakens dietary diversity and nutritional quality. In addition, persistent food inflation can place pressure on government food subsidy programs and public distribution systems. Therefore, the

impacts of El Niño extend beyond agricultural production, directly influencing food security, nutritional well-being, consumer welfare, and overall economic stability in the country.

Impact on farmers' income, investment capacity and agricultural economy: El Niño can have significant economic consequences for farmers by reducing agricultural productivity and increasing production costs. Deficient or erratic rainfall often leads to lower crop yields, crop failures, and reduced marketable surplus, directly affecting farm incomes. At the same time, farmers may be required to spend more on irrigation, water pumping, drought-mitigation measures, crop protection, and additional agricultural inputs to cope with adverse weather conditions. These increased costs, combined with lower production, reduce overall farm profitability.

Small and marginal farmers are particularly vulnerable because they possess limited financial resources, smaller landholdings, and restricted access to irrigation and institutional credit. A decline in income can force them to cut back on investments in quality seeds, fertilizers, machinery, and improved technologies for the subsequent cropping season. Such reductions in agricultural investment may adversely affect future productivity and hinder the adoption of modern farming practices.

Financial stress caused by El Niño can also increase farmers' dependence on credit and make repayment of agricultural loans more difficult. In severe situations, prolonged income losses may lead to indebtedness and economic insecurity. The effects extend beyond individual farmers to local markets, agro-based industries, input suppliers, traders, and rural service sectors, all of which depend on agricultural prosperity. Consequently, El Niño not only affects a single agricultural season but can also slow long-term agricultural growth, weaken rural economic development, and reduce the overall resilience of the agricultural economy.

Broader Impact on the National Economy: The significance of Indian agriculture extends far beyond food production, as it serves as a foundation for employment, rural livelihoods, industrial development, and overall economic growth. A large proportion of India's population depends directly or indirectly on agriculture for income and employment. Consequently, any adverse impact of El Niño on agricultural production can have far-reaching consequences for the national economy.

During El Niño years, deficient or erratic monsoon rainfall often leads to lower crop yields, reduced farm incomes, and increased production costs. As farmers experience financial stress, their purchasing power declines, resulting in lower rural consumption. This reduction in demand can negatively affect sectors such as consumer goods, transportation, manufacturing, and agricultural input industries, thereby slowing economic activity in rural and semi-urban areas.

El Niño-induced production shortfalls can also lead to food shortages and higher prices of essential commodities. Rising food inflation places pressure on household budgets and may compel policymakers to adopt monetary measures to control inflation. At the same time, governments may need to increase expenditure on food procurement, public distribution systems, crop insurance, drought relief, and agricultural support programs. Such expenditures can strain public finances and divert resources from other developmental priorities. Therefore, the effects of El Niño are not confined to agriculture alone; they influence economic stability, inflation management, employment generation, and overall national development, making it a significant macroeconomic concern for India.

Holistic Perspective

El Niño represents a multifaceted and systemic risk to Indian agriculture, influencing nearly every component of the agricultural and rural economy. Its impacts extend far beyond crop production, affecting water resources, soil health, livestock productivity, fisheries, rural employment, food security, nutritional well-being, and farmers' livelihoods. Reduced and erratic rainfall during El Niño years often leads to drought conditions, moisture stress, lower crop yields, depletion of groundwater reserves, and increased dependence on irrigation. Simultaneously, higher temperatures and prolonged dry spells intensify heat stress on crops and livestock, reduce water-use efficiency, and accelerate land degradation processes.

The adverse effects of El Niño are particularly severe for small and marginal farmers, who constitute the majority of India's farming community. Limited access to irrigation, credit, insurance, and modern technologies reduces their capacity to cope with climatic shocks and market fluctuations. Declining agricultural productivity can lower farm incomes, weaken rural demand, and adversely affect agro-based industries and local economies.

In the context of ongoing climate change, the frequency, intensity, and unpredictability of extreme weather events are expected to increase, making the impacts of El Niño more complex and difficult to manage. (Fig 4). Therefore, India needs a comprehensive and integrated strategy that combines climate-resilient crop varieties, efficient water management, soil conservation, diversified farming systems, weather-based advisory services, digital technologies, crop insurance, and strong institutional support. Investments in agricultural research, climate forecasting, and rural infrastructure are equally important. Such a holistic approach will enhance agricultural resilience, strengthen food and nutritional security, improve farmers' incomes, and ensure sustainable agricultural development in the face of future El Niño events and other emerging global challenges.

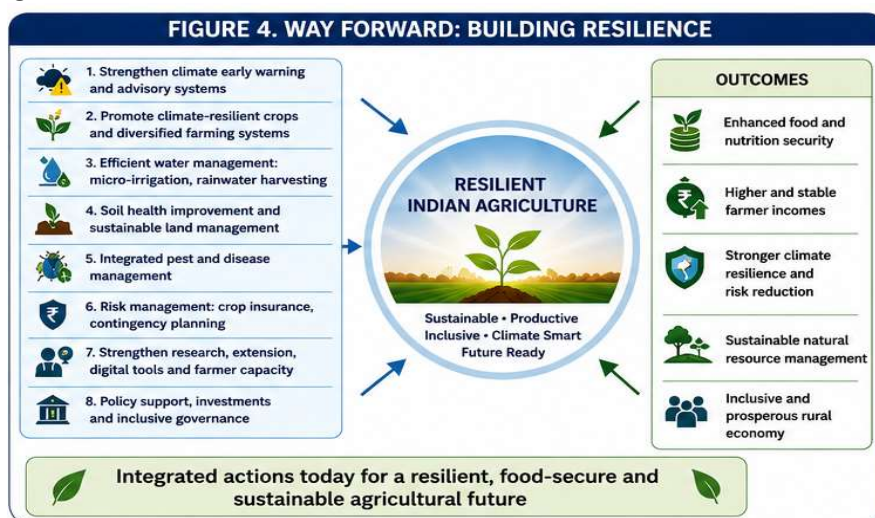


Fig. 4 Way Forward: Building Resilience

Summary and Conclusion

Indian agriculture is highly dependent on climatic conditions and remains particularly vulnerable to climate variability and extreme weather events. This paper examined the interconnected effects of El Niño, climate change, and emerging global uncertainties on Indian agriculture. El

Niño-induced disruptions in monsoon patterns frequently lead to rainfall deficits, droughts, heat waves, and water scarcity, adversely affecting crop production, agricultural productivity, and farmers' livelihoods. Simultaneously, long-term climate change has intensified the frequency and severity of extreme weather events, including irregular rainfall, floods, rising temperatures, and prolonged dry spells, creating additional challenges for agricultural sustainability. The study further highlighted how global uncertainties such as geopolitical conflicts, energy price fluctuations, supply-chain disruptions, and market volatility influence agricultural input costs, food security, and farm incomes. These combined pressures have significant implications for crop yields, water resources, livestock production, and the overall resilience of India's agrarian economy.

Despite these challenges, Indian agriculture possesses considerable adaptive potential. Strengthening climate-resilient farming systems, promoting drought- and heat-tolerant crop varieties, improving water-use efficiency, expanding weather-based advisory services, enhancing crop insurance coverage, and investing in climate-smart agriculture can substantially reduce vulnerability. Greater integration of scientific forecasting, digital technologies, sustainable resource management, and policy support will be essential for building resilience against future climatic and global shocks.

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FROM BATCH TO EVIDENCE: A QUALITY-ASSURANCE FRAMEWORK FOR EVALUATING DE-OILED RICE BRAN IN ANIMAL FEED

Ankit Bansal

Director - Business Development, Rudrapur Solvents Private Limited

*Corresponding Email: ankitbansal@rudrapursolvents.com

Abstract

De-oiled rice bran (DORB) is often evaluated through a single laboratory value, most commonly crude protein. That approach is insufficient for research, formulation and procurement. This article presents a practical quality-assurance framework centred on representative sampling, multi-parameter interpretation, storage control and batch traceability. It is intended to help students, researchers and feed professionals assess DORB as a reproducible feed ingredient rather than a variable raw material.

Keywords: de-oiled rice bran; DORB; feed quality assurance; representative sampling; traceability; animal nutrition.

Introduction

De-oiled rice bran (DORB) is the solid material remaining after oil extraction from rice bran. As a rice-processing co-product, it has a legitimate place in animal-feed systems when its quality is understood and its use is formulated responsibly. Yet DORB is sometimes discussed as though a protein number alone can describe the material. For scientific work and practical feed manufacture, that is too narrow. A feed ingredient is not simply its average composition; it is also the consistency of the batch, the way it was sampled, the condition in which it was stored and the evidence available to support the values used in formulation.

Why quality assurance matters

DORB can vary because of the raw bran, pre-cleaning, extraction conditions, post-process handling, transport and storage. This does not make the ingredient unsuitable. It means the ingredient must be evaluated through a system. If two batches have similar crude protein but differ materially in fibre, moisture or insoluble mineral matter, they may not contribute the same usable nutrients to a complete diet. A research result or commercial formulation that does not document this variation can be difficult to interpret or reproduce.

The most useful question is therefore not, 'What is the protein percentage?' but, 'Does the full quality pattern support the intended nutritional role?' The answer should be based on a batch-specific report, physical inspection, sound sampling and the judgement of the nutrition professional responsible for the final ration.

Sampling is the first scientific control

A laboratory result cannot be better than the sample submitted to the laboratory. A handful taken from one convenient bag may miss variation across a truck, stack or production lot. For a representative composite sample, small portions should be drawn from multiple bags and different positions, mixed in a clean container and reduced carefully for testing. A sealed retained sample should also be kept with the lot number, date and supplier details. This creates a reference point if later observations do not match the original analysis.

For student projects and feeding trials, sampling discipline is especially important. The material used in the trial should be identified by batch, analysed before use and described in the methods section. Without those controls, a conclusion attributed to DORB may actually reflect an unrecorded difference in fibre, moisture, mineral contamination or storage history.

Read the report as a pattern, not a headline

Crude protein remains an important parameter, but it should be read alongside crude fibre, moisture, total ash, acid-insoluble ash (AIA), sand/silica indicators and, where relevant, residual oil, aflatoxin and other safety tests. These parameters answer different questions. Fibre relates to bulk and digestibility; moisture affects storage stability; total ash describes the total mineral residue; and AIA is useful for detecting largely indigestible mineral contamination such as sand and silica. No single result establishes quality on its own.

Parameter	What it helps indicate	Why it matters in evidence-based use
Crude protein	A starting estimate of nitrogen-derived protein.	Should be interpreted with digestibility, processing history and the complete nutrient profile.
Crude fibre	The fibrous fraction and possible dilution by fibrous material.	Influences energy density and can affect how an ingredient fits a species- and stage-specific formula.
Moisture	Storage stability and risk of caking or spoilage.	A sound analysis can lose relevance if the material absorbs moisture after receipt.
Total ash and AIA	Overall mineral residue and largely insoluble mineral contamination.	Helps distinguish useful mineral content from non-nutritive material that adds weight but little feeding value.
Physical checks	Odour, flow, colour, clumping and visible contamination.	Provides a practical cross-check against the report before a batch enters a trial or production system.

A high value in one parameter should prompt questions rather than automatic conclusions. For example, total ash by itself does not prove poor quality, because feed ingredients naturally contain minerals. However, elevated ash together with elevated AIA and a gritty physical feel warrants closer examination. Similarly, a satisfactory protein result does not compensate for excessive moisture or a musty odour. The strength of the quality assessment lies in combining the evidence.

Storage is part of ingredient quality

Ingredient quality does not stop at the factory gate. DORB is an organic, moisture-absorbing material, so storage conditions can alter its suitability after purchase. Bags should be kept on pallets, protected from rain and floor moisture, separated from walls, and arranged to permit inspection and airflow. First-in, first-out rotation, clear lot labels and regular checks for clumping, heating or unusual odour are simple controls with significant value.

For research, storage should be reported just as carefully as diet preparation. If material is stored for a prolonged period or under humid conditions, re-testing may be appropriate before it is used. This is not merely a warehouse practice; it is a way of protecting the validity of the data generated from the ingredient.

A framework for research and formulation

Before DORB is included in a study or a feed programme, four records should travel with the batch: a purchase specification, a representative laboratory report, a physical-receipt record and a storage/traceability record. These documents make it easier to compare lots, investigate unexpected performance and communicate transparently among procurement, quality control, researchers and nutritionists.

The final decision must still be made within the complete diet. DORB is not a one-to-one replacement for another ingredient, and there is no universal inclusion level suitable for every species, age, production target or local raw-material situation. The ration should be balanced by a qualified nutritionist using the actual batch analysis, the nutrient contribution credited to the ingredient and the needs of the animal.

Conclusion

DORB deserves to be studied and used as a measurable feed ingredient, not treated as a generic low-cost byproduct. The strongest quality practice begins with representative sampling, continues with multi-parameter analysis and storage discipline, and ends with transparent batch records. This approach improves both scientific reproducibility and practical feeding decisions. It also moves the discussion away from a single attractive number and toward the more important question: whether the evidence supports dependable use in the intended diet.

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**VEDIC YAGYA: AN ETERNAL CONVERGENCE OF SPIRITUALITY,
SCIENCE, AND AGRICULTURAL SUSTAINABILITY****K.N. Tiwari**

Senior Agricultural Scientist, 4/861, Gomti Nagar Extension, Lucknow 226010

*Corresponding Email: kashinathtiwari730@gmail.com**Abstract**

Vedic Yagya is not merely a religious ritual; it is a comprehensive philosophy of life that harmoniously integrates spirituality, nature, environmental stewardship, agriculture, and human welfare. Rooted in the Vedic tradition, Yagya symbolizes selfless sacrifice, collective responsibility, gratitude toward nature, and the pursuit of the common good. It teaches that human beings are an integral part of the natural world and must maintain a balanced relationship with the environment for sustainable existence. The principles of Yagya encourage cooperation, discipline, moral values, and social harmony while fostering a sense of duty toward society and future generations. Traditionally, Yagya has been associated with ecological balance, agricultural prosperity, purification of the atmosphere, and community well-being. In the present era, marked by environmental degradation, climate change, social conflicts, and ethical challenges, the philosophy of Yagya offers valuable guidance for sustainable development, mental peace, environmental conservation, and global welfare. Its timeless message inspires humanity to work collectively for a healthier, more harmonious, and sustainable future. Vedic Yagya is not merely a religious ritual, but a philosophy of life that integrates nature, the environment, agriculture, and human welfare. It strengthens the spirit of sacrifice, cooperation, gratitude, and public welfare. Amidst today's environmental and ethical challenges, the concept of Yagya offers an inspiring path to sustainable development, social harmony, mental peace, and global welfare. This paper examines the significance of Vedic Yagya in nature conservation, environmental protection, agriculture, and human welfare. It explores scriptural references and their relevance from modern scientific perspectives, highlighting how Yagya's principles can promote ecological sustainability, social harmony, and holistic well-being in contemporary society.

Introduction

Yagya occupies a central and revered position in Indian culture and civilization. Since Vedic times, it has been regarded as the foundation of religion, social harmony, environmental balance, agricultural prosperity, and human well-being. The significance of Yagya has been extensively described in the Vedas, Upanishads, Puranas, Ramayana, Mahabharata, and the Srimad Bhagavad Gita. These sacred texts portray Yagya not merely as a ritualistic offering into the sacred fire but as a profound philosophy that promotes selfless action, gratitude toward nature, and collective welfare. The Puranas, in particular, emphasize Yagya as a means of maintaining harmony between humans, nature, and the divine forces governing the universe.

Ancient Indian sages and scholars viewed Yagya as a scientific and spiritual practice capable of sustaining ecological balance and enhancing the quality of life. The offerings used in Yagya, including medicinal herbs, clarified butter (ghee), fragrant woods, and other natural substances, were believed to purify the atmosphere and create a healthy environment. Yagya was also considered beneficial for agriculture by promoting favourable climatic conditions, rainfall, and soil fertility, thereby supporting food production and rural livelihoods.

In recent years, modern scientific investigations have begun to explore the environmental and health-related effects of Yagya. Studies suggest that the combustion of specific herbal ingredients may possess antimicrobial properties, contribute to air purification, and promote psychological well-being through the combined effects of aromatic substances and mantra chanting. Thus, Yagya represents a unique and timeless convergence of spirituality, environmental consciousness, agricultural sustainability, and scientific wisdom, making it highly relevant in addressing contemporary environmental and societal challenges. The purpose of this paper is to examine the significance of Vedic Yagya in the context of nature, environmental protection, agriculture, and human welfare. It aims to explore the references to Yagya in ancient Indian scriptures and evaluate its relevance through modern scientific perspectives. The paper also highlights how the principles of Yagya can contribute to ecological sustainability, social harmony, and holistic well-being in the contemporary world.

Yagya: A Sacred Bridge Between Humanity, Nature, and the Divine

Yagya occupies a central position in Indian culture, philosophy, and Sanatan Dharma. Since the earliest Vedic period, it has been regarded as the foundation of religious life, social harmony, environmental balance, and human welfare. The concept of Yagya extends far beyond the ritual act of offering oblations into a sacred fire. In the broader Vedic worldview, Yagya represents a way of life founded on sacrifice, selfless service, dedication, gratitude, cooperation, and the pursuit of collective well-being. Ancient Indian sages viewed Yagya as a powerful means of self-purification, social cohesion, ecological balance, and spiritual advancement. Consequently, references to Yagya are found throughout the Vedas, Upanishads, Puranas, Ramayana, Mahabharata, and the Srimad Bhagavad Gita, where it is portrayed as an essential principle governing the harmonious functioning of both human society and the natural world. The significance of Yagya is evident from the very opening mantra of the Rigveda, the oldest known scripture of humanity:

“Agnimīle Purohitam Yajñasya Devam Rtvijam” (Rigveda 1.1.1)

This mantra invokes Agni (fire) as the divine priest of the Yagya and the mediator between human beings and the divine powers. In Vedic thought, Agni symbolizes transformation, purification, and communication. Through the sacred fire, offerings made by human beings are believed to reach the divine realm, thereby maintaining harmony between humans, nature, and cosmic forces. Thus, the Vedic concept of Yagya embodies the principle of mutual cooperation and interdependence among all components of existence.

The Upanishads further expanded the meaning of Yagya beyond external rituals and emphasized its inner spiritual significance. They taught that true Yagya involves the sacrifice of ego, selfishness, ignorance, and negative tendencies. In this sense, every selfless act performed for the welfare of others becomes a form of Yagya. The transformation of human consciousness through discipline, knowledge, and service was regarded as the highest form of sacrifice. Therefore, Yagya evolved from a ritualistic practice into a comprehensive ethical and spiritual philosophy.

The Bhagavad Gita provides one of the most profound interpretations of Yagya. Lord Krishna explains that all actions performed with a spirit of selflessness and dedication become Yagya. He states:

“Yajñārthāt Karmaṇo'nyatra Loko'yam Karma-bandhanah” (Bhagavad Gita 3.9)

This verse means that actions performed solely for personal gain create bondage, whereas actions performed in the spirit of Yagya liberate the individual. Here, Yagya symbolizes selfless action,

duty, and service to society. The teaching forms the foundation of Karma Yoga, which encourages individuals to perform their responsibilities without attachment to personal rewards.

The Bhagavad Gita also highlights the intimate relationship between Yagya, nature, and human survival:

“Annād Bhavanti Bhūtāni Parjanyaḥ Anna-sambhavaḥ; Yajñād Bhavati Parjanya Yajñaḥ Karma-samudbhavaḥ” (Bhagavad Gita 3.14)

According to this verse, all living beings depend on food, food depends on rainfall, rainfall depends on Yagya, and Yagya arises from righteous action. This teaching presents a profound ecological philosophy. The term “Yagya” here should not be interpreted merely as a ritual sacrifice but as the collective practice of responsible, ethical, and environmentally conscious living. When humans act in harmony with nature, conserve natural resources, protect forests, maintain biodiversity, and avoid environmental degradation, ecological balance is preserved, resulting in favorable climatic conditions and sustainable food production. Thus, the Gita establishes a direct connection between moral conduct, environmental stewardship, and human welfare. The Ramayana also contains several important references to Yagya. In the Valmiki Ramayana, King Dasharatha, desiring offspring, approaches Sage Rishya Shringa, who performs the Putrakameshti Yagya. The sage declares:

“Iṣṭiṁ Te'haṁ Kariṣyāmi Putrīyāṁ Putrakāraṇāt” meaning, “I shall perform the sacred sacrifice that will fulfill your desire for sons.” As a result of this Yagya, Lord Rama, Bharata, Lakshmana, and Shatrughna were born. Beyond its literal narrative significance, this episode illustrates the belief that Yagya generates positive and auspicious outcomes when performed with sincerity and noble intentions. Similarly, in Goswami Tulsidas’s Ramcharitmanas, the Putrakameshti Yagya occupies an important place in the divine narrative of Lord Rama’s incarnation. Furthermore, the episode of Lord Rama protecting the Yagya of Sage Vishwamitra symbolizes the preservation of righteousness, spiritual traditions, and cultural values against disruptive forces. This narrative highlights the importance of safeguarding the principles that sustain social and cosmic order.

The Mahabharata likewise underscores the significance of Yagya in governance, social responsibility, and public welfare. After the Kurukshetra war, Yudhishtira performed the Ashwamedha Yagya to restore social order and establish righteous governance. Earlier, the Rajasuya Yagya had served as a symbol of legitimate authority and collective prosperity. However, the Mahabharata repeatedly emphasizes that the true value of Yagya lies not in external grandeur or ritual display but in the purity of intention and commitment to dharma. A Yagya devoid of ethical conduct and compassion loses its true spiritual significance. The Puranas further reinforce the importance of Yagya as the foundation of dharma and cosmic harmony. Numerous Puranic narratives describe Yagya as a means of maintaining balance between divine, natural, and human realms. The Srimad Bhagavata Mahapurana states:

“Yajñaiḥ Saṅkīrtana-prāyair Yajanti Hi Sumedhasaḥ” (11.5.32)

This verse explains that in the age of Kali, wise individuals worship the Divine primarily through the Yagya of devotional chanting and remembrance of God's name. Here again, the concept of Yagya is broadened beyond ritual sacrifice to include devotion, spiritual discipline, and collective worship. Such interpretations demonstrate the adaptability of the Yagya principle across different historical and cultural contexts.

In essence, the scriptural literature of India presents Yagya as a multidimensional concept encompassing religious, ethical, ecological, social, and spiritual dimensions. It is a symbol of selfless service, environmental responsibility, gratitude toward nature, and commitment to the welfare of all beings. The underlying philosophy of Yagya encourages individuals to contribute positively to society, preserve ecological balance, and pursue spiritual growth through righteous action. In an era characterized by environmental crises, social fragmentation, and ethical challenges, the timeless wisdom of Yagya offers valuable guidance for fostering sustainable development, social harmony, and universal well-being. Thus, within the Vedic and scriptural tradition, Yagya remains a powerful and enduring symbol of harmony between humanity, nature, and the divine.

Yagya and Nature: A Timeless Path to Environmental Harmony

In the Indian Vedic tradition, Yagya is not merely a religious ritual but also an important means of establishing harmony between nature and humanity. Ancient scriptures, including the Vedas, Upanishads, Bhagavad Gita, Ramayana, Mahabharata, and various Puranas, emphasize the role of Yagya in maintaining ecological balance, promoting social welfare, and conserving natural resources. The Vedic worldview recognizes that human well-being is inseparably connected with the health of the natural environment, and Yagya serves as a symbolic and practical expression of this interconnectedness.

During the performance of Yagya, various natural substances such as ghee, guggulu, sandalwood, camphor, cardamom, cloves, peepal leaves, mango wood (samidha), and medicinal herbs are offered into the sacred fire. As these substances burn, they are dispersed into the atmosphere in the form of fine particles and aromatic compounds. Traditional Vedic literature maintains that these materials help purify the air and create a healthy environment. Modern scientific investigations have also explored the effects of medicinal smoke generated during Yagya and have reported its potential antimicrobial properties, indicating a reduction in certain airborne microorganisms. Although further research is needed to establish its large-scale environmental impact, such findings suggest that traditional practices may possess ecological significance.

In the contemporary era, environmental degradation has emerged as a global concern. Air pollution, industrial emissions, greenhouse gases, deforestation, and the depletion of natural resources pose serious threats to human health and ecological sustainability. In this context, the environmental philosophy underlying Yagya offers valuable insights. The practice encourages moderation in consumption, respect for natural resources, and a sense of responsibility toward the environment. It promotes the idea that humans should act as custodians rather than exploiters of nature.

The scriptural statement “Yagyaad Bhavati Parjanyaah” (from Yagya comes rainfall) is often interpreted in a broader ecological sense. It signifies that when human activities remain aligned with natural laws and environmental ethics, ecological processes such as the water cycle, rainfall patterns, and biodiversity remain balanced. Responsible actions such as tree conservation, water management, soil protection, and pollution control reflect the true spirit of Yagya.

Furthermore, Indian culture developed traditions of reverence for trees such as *Peepal*, *Banyan*, *Neem*, and *Tulsi*, recognizing their ecological and medicinal value. These practices foster environmental awareness, biodiversity conservation, and sustainable living. Thus, Yagya represents not only a spiritual discipline but also a timeless ecological philosophy that encourages

harmony between humanity and nature, making it highly relevant for addressing contemporary environmental challenges and promoting sustainable development.

Vedic Yagya: Bridging Agriculture, Ecology, and Human Well-Being

Yagya occupies a special and significant place in the Indian agricultural tradition. Since ancient times, agriculture has been regarded not merely as an economic activity but as a sacred responsibility closely connected with nature and human survival. The Vedic worldview recognized that successful agriculture depends upon the harmonious interaction of natural elements such as soil, water, air, sunlight, and biodiversity. Therefore, before commencing agricultural activities, farmers traditionally performed land worship (Bhumi Pujan) and Yagya to express gratitude toward nature and seek blessings for a healthy and abundant harvest. These practices reflected a deep understanding of humanity's dependence on natural resources and promoted a respectful relationship between agriculture and the environment.

In Vedic culture, Yagya symbolized the principle of reciprocity between humans and nature. It emphasized that while humans derive sustenance from natural resources, they also have a responsibility to protect and preserve them. Through Yagya, people acknowledged the contributions of the five basic elements - earth, water, fire, air, and space in sustaining agricultural productivity and ecological balance. This philosophy encouraged responsible use of resources, conservation of biodiversity, and sustainable farming practices long before the emergence of modern environmental science.

The by-products of Yagya, particularly Yagya ash, have traditionally been considered beneficial for agricultural fields. Farmers often incorporated the ash into the soil because it contains minerals such as potassium, calcium, magnesium, and other micronutrients that may contribute to soil fertility. The ash can also help improve soil structure and support nutrient cycling. Although the effectiveness of Yagya ash depends on the materials used and local soil conditions, its application reflects an indigenous approach to recycling organic resources and maintaining soil health.

In recent decades, excessive dependence on chemical fertilizers, pesticides, and intensive farming practices has led to several environmental challenges, including soil degradation, loss of soil biodiversity, declining organic matter, groundwater contamination, and reduced ecosystem resilience. As a result, there is growing interest worldwide in sustainable, organic, and regenerative agricultural systems. In this context, traditional practices inspired by Yagya, such as Agnihotra agriculture, have attracted attention for their emphasis on natural resource management, soil health, and ecological balance. Agnihotra farming utilizes Yagya ash along with organic inputs to support plant growth and improve soil quality while minimizing environmental harm.

Rainfall remains one of the most critical factors determining agricultural productivity, particularly in rainfed farming regions. Ancient scriptures associate Yagya with rainfall through the concept expressed in the phrase "Yagyaad Bhavati Parjanyaah," which symbolically highlights the connection between human actions and ecological balance. Sustainable management of forests, water resources, soil, and biodiversity helps maintain healthy ecosystem functions, including the hydrological cycle and rainfall patterns. Thus, the broader philosophy of Yagya emphasizes environmental stewardship as a prerequisite for agricultural prosperity.

Today, agriculture faces unprecedented challenges from climate change, droughts, floods, erratic rainfall, land degradation, and declining natural resources. Addressing these challenges requires

approaches that integrate productivity with environmental sustainability. The principles embodied in Yagya respect for nature, conservation of resources, ecological balance, and collective responsibility offer valuable guidance for developing resilient agricultural systems. Therefore, Yagya should be understood not merely as a religious ritual but as a holistic cultural and philosophical framework that supports sustainable agriculture, environmental conservation, food security, and long-term human well-being.

Yagya and Human Well-Being: A Holistic Path to Physical, Mental, Social, and Spiritual Harmony

In the Vedic tradition, Yagya is regarded as a comprehensive system for promoting human welfare and holistic development. Far beyond being a ritualistic fire ceremony, Yagya embodies a philosophy that nurtures physical health, mental peace, social harmony, and spiritual growth. Ancient Indian sages viewed Yagya as a means of creating balance within the individual and society while fostering a harmonious relationship with nature. Its principles continue to hold relevance in the modern world, where humanity faces increasing challenges related to stress, social fragmentation, environmental degradation, and declining moral values.

One of the most significant aspects of Yagya is its contribution to mental and emotional well-being. The chanting of Vedic mantras, meditation, and collective prayers form integral components of Yagya. According to traditional belief, the sacred vibrations generated by mantra recitation create a positive atmosphere and help purify the mind. Modern scientific studies on meditation and rhythmic chanting suggest that these practices may enhance concentration, reduce anxiety, regulate breathing patterns, and promote relaxation. In today's fast-paced and highly competitive society, where stress, depression, and mental unrest are becoming increasingly common, practices associated with Yagya can contribute to mental balance, emotional resilience, and positive thinking.

Yagya also serves as a powerful instrument for strengthening social cohesion and collective responsibility. Historically, Yagyas were community-centered events that brought together people from different social and economic backgrounds. Participation in such gatherings encouraged cooperation, mutual respect, and a shared commitment to the common good. Charity, service, philanthropy, and assistance to the underprivileged were regarded as essential elements of Yagya. These values fostered social harmony and reinforced the idea that individual well-being is closely connected with the welfare of society. The spirit of selfless service promoted through Yagya remains highly relevant in addressing contemporary social challenges and building inclusive communities.

From a health perspective, Yagya has traditionally been associated with environmental purification and the promotion of a healthy living environment. Substances such as ghee, guggulu, camphor, sandalwood, and various medicinal herbs are offered into the sacred fire during the ritual. The resulting aromatic smoke has long been considered beneficial for creating a pleasant and purified atmosphere. Ayurveda also describes Dhupana therapy, which utilizes medicinal smoke for environmental cleansing. Some scientific investigations have indicated that certain forms of medicinal smoke may reduce the concentration of specific microorganisms in the surrounding environment, although further research is needed to establish its broader health effects.

From a spiritual standpoint, Yagya symbolizes sacrifice, self-discipline, gratitude, and dedication to a higher purpose. It teaches individuals to transcend selfish interests and contribute toward the

welfare of society, nature, and future generations. By cultivating values such as compassion, responsibility, and selflessness, Yagya promotes ethical living and inner transformation. Thus, Yagya represents a timeless and holistic approach to human welfare, integrating environmental awareness, social harmony, mental peace, physical well-being, and spiritual enrichment for the betterment of humanity.

Reintegrating Vedic Wisdom with Modern Agriculture for a Sustainable Future

The contemporary world faces unprecedented challenges arising from climate change, environmental degradation, biodiversity loss, soil depletion, water scarcity, and growing concerns about human health and well-being. Modern agriculture, while significantly enhancing food production, has often relied on intensive use of chemical fertilizers, pesticides, and natural resources, leading to ecological imbalances and declining sustainability. In this context, the ancient Vedic concept of Yagya offers valuable insights that can complement modern scientific approaches and contribute to the development of a more resilient and sustainable future.

Throughout Indian civilization, Yagya has symbolized a harmonious relationship between humanity, nature, and the divine. It embodies the principles of selfless service, environmental stewardship, gratitude toward natural resources, and collective welfare. While Yagya has traditionally been viewed as a sacred ritual, its deeper significance lies in its philosophy of maintaining balance within ecological, social, and spiritual systems. These principles are remarkably relevant to contemporary efforts aimed at achieving sustainable development and environmental conservation.

The integration of Yagya-inspired values with modern farming practices presents a promising pathway for sustainable agriculture. The concept of Yagya encourages respect for soil, water, forests, biodiversity, and all living beings. Such an approach aligns closely with the principles of regenerative agriculture, organic farming, conservation agriculture, integrated farming systems, and climate-smart agriculture. Practices such as recycling organic residues, enhancing soil organic matter, conserving water resources, promoting biodiversity, and reducing dependence on synthetic agrochemicals reflect the spirit of Yagya in modern agricultural systems.

Particular attention may be given to the scientific evaluation of traditional practices associated with Yagya, including the use of Yagya ash, Agnihotra-based farming, and herbal preparations. While rigorous scientific validation remains necessary, these practices offer opportunities for interdisciplinary research linking traditional ecological knowledge with modern agricultural science. Future studies may explore their potential effects on soil fertility, microbial diversity, crop productivity, environmental quality, and ecosystem resilience. Such investigations can help distinguish symbolic practices from scientifically applicable innovations while preserving valuable indigenous knowledge systems.

Beyond agricultural productivity, the philosophy of Yagya provides a broader ethical framework for sustainable living. It teaches that human prosperity cannot be achieved through the exploitation of nature but through cooperation with natural processes. The Vedic principle of “Yajñārthāt Karma” emphasizes responsible action undertaken for the welfare of society and future generations. This perspective is particularly relevant at a time when global sustainability efforts increasingly recognize the need to integrate ecological responsibility with economic development.

Yagya also contributes to human welfare by promoting mental peace, social cohesion, ethical conduct, and environmental consciousness. Collective participation in activities inspired by Yagya can strengthen community engagement, encourage resource conservation, and foster a shared commitment to environmental stewardship. Such values are essential for addressing contemporary challenges that extend beyond technology and require changes in human attitudes and behavior. In conclusion, Vedic Yagya represents far more than a religious tradition; it is a timeless philosophy that integrates spirituality, science, sustainability, and human welfare. Its teachings emphasize harmony between humans and nature, responsible resource use, social responsibility, and ecological balance. By thoughtfully integrating the enduring wisdom of Yagya with modern scientific knowledge and sustainable agricultural practices, humanity can move toward a future that is productive, environmentally sound, socially equitable, and spiritually enriched. Thus, Vedic Yagya continues to offer an eternal convergence of spirituality, science, and sustainability, providing inspiration for building a healthier planet and a more harmonious society.

Summary and Conclusion

Vedic Yagya represents a unique synthesis of spirituality, environmental consciousness, agricultural sustainability, and human welfare. Ancient Indian scriptures, including the Vedas, Upanishads, Ramayana, Mahabharata, Bhagavad Gita, and Puranas, describe Yagya not merely as a ritual but as a holistic philosophy based on sacrifice, selfless service, ecological balance, and collective well-being. The principles of Yagya emphasize harmony between humans and nature, responsible use of natural resources, conservation of biodiversity, and the promotion of social and moral values. In the contemporary era of climate change, environmental degradation, declining soil health, and increasing social and psychological challenges, the philosophy of Yagya offers valuable guidance for sustainable development. Its emphasis on environmental stewardship, community cooperation, ethical living, and respect for nature aligns closely with modern concepts of sustainability and regenerative agriculture. Therefore, Yagya should be viewed as a timeless source of inspiration that can help foster ecological resilience, agricultural prosperity, human well-being, and a more harmonious relationship between humanity and the natural world.

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DIGITAL EXTENSION SERVICES FOR FISH FARMERS: TRANSFORMING AQUACULTURE THROUGH SMART INFORMATION TECHNOLOGIES

Ankit Yadav* and Anupam Anand

College of Fisheries Science, Hisar, CCSHAU, Haryana-125004

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Aquaculture is one of the fastest-growing food production sectors, contributing significantly to global food security, employment generation, and rural livelihoods. However, sustainable aquaculture development requires timely access to scientific knowledge, technical guidance, and effective farm management strategies. Digital extension services have emerged as a promising approach to bridge the information gap between researchers, extension professionals, and fish farmers through the use of information and communication technologies (ICTs). Digital tools such as mobile applications, online advisory platforms, artificial intelligence (AI), Internet of Things (IoT)-based monitoring systems, and digital marketplaces are improving access to information on water quality management, fish nutrition, disease prevention, weather advisories, and market opportunities. These technologies enable faster decision-making, improve farm productivity, reduce production risks, and support climate-resilient aquaculture practices. Despite their potential, challenges including limited internet connectivity, digital literacy, language barriers, and inadequate infrastructure continue to restrict widespread adoption, particularly among small-scale farmers. Strengthening digital infrastructure, promoting farmer training, and integrating digital tools with conventional extension systems are essential for maximizing their benefits. This article highlights the role, applications, benefits, challenges, and future prospects of digital extension services in transforming modern aquaculture.

Keywords: Digital extension, Aquaculture, ICT, Artificial intelligence, Internet of Things, Fish farmers, Sustainable aquaculture

Introduction

Aquaculture has emerged as a key sector of global food production, contributing to food security, employment, and economic development. With increasing demand for aquatic products, sustainable intensification of aquaculture requires improved access to scientific knowledge, efficient resource management, and adoption of innovative farming practices (FAO, 2022). Conventional aquaculture extension services have traditionally supported knowledge transfer through field visits, demonstrations, training programmes, and advisory activities. However, limitations such as inadequate extension personnel, geographical barriers, and delayed information delivery often restrict their effectiveness, particularly among small-scale farmers (Kumaran *et al.*, 2011). Advances in information and communication technologies (ICTs) have introduced digital extension services as an effective approach for improving knowledge dissemination in aquaculture. Digital platforms, mobile applications, artificial intelligence (AI), Internet of Things (IoT), and online advisory systems provide farmers with real-time information on pond management, water quality, fish health, feeding practices, weather conditions, and markets (FAO, 2018; Mahalakshmi *et al.*, 2014). These technologies support precision aquaculture

through real-time monitoring, data-based decision-making, and early detection of production challenges, thereby improving efficiency, profitability, and sustainability. However, challenges related to digital literacy, connectivity, infrastructure, and access to reliable information must be addressed for wider adoption. This article highlights the role, applications, benefits, challenges, and future prospects of digital extension services in promoting sustainable and technology-driven aquaculture.

What are Digital Extension Services?

Digital extension services are technology-enabled advisory systems that deliver timely, accurate, and location-specific information to fish farmers through information and communication technologies (ICTs). Using smartphones, mobile applications, websites, SMS, social media, online videos, and virtual training platforms, these services provide scientific guidance on pond preparation, water quality management, fish nutrition, disease prevention, harvesting, marketing, and other aquaculture practices (Kumaran *et al.*, 2011; FAO, 2018). Unlike conventional extension, which primarily depends on field visits, demonstrations, training programmes, and printed materials, digital extension enables rapid, cost-effective, and continuous dissemination of technical information. Farmers can receive real-time updates on weather conditions, disease outbreaks, market prices, and government schemes, allowing them to make informed management decisions while overcoming constraints such as limited extension personnel, geographical barriers, and delays in information delivery (FAO, 2018; Byamukama *et al.*, 2025). The primary objective of digital extension services is to bridge the gap between scientific research and on-farm practices by ensuring that reliable information reaches farmers in an accessible and user-friendly format. By promoting evidence-based decision-making, these services improve fish health management, optimize feeding and water quality practices, enhance market access, reduce production risks, and contribute to higher productivity, increased farm income, and sustainable, climate-resilient aquaculture (FAO, 2018; ICAR, 2024).

Major Digital Technologies Used in Aquaculture

Advancements in digital technologies have significantly transformed aquaculture practices by improving access to scientific information, farm monitoring, disease management, and decision-making. Various digital tools now support farmers in adopting efficient, precise, and sustainable aquaculture practices (FAO, 2022; Mahalakshmi *et al.*, 2014).

Mobile Applications

Mobile applications provide farmers with easy access to information on pond preparation, water quality management, fish nutrition, disease identification, weather conditions, market prices, and government schemes, enabling timely and informed decisions (Mahalakshmi *et al.*, 2014; FAO, 2022).

SMS and Voice Advisory Services

SMS and voice-based advisory systems deliver timely alerts on weather conditions, disease outbreaks, feeding practices, and farm management in local languages. These services are particularly valuable in areas with limited internet connectivity (FAO, 2018; Byamukama *et al.*, 2025).

Social Media and Online Communication Platforms

Platforms such as WhatsApp, Telegram, Facebook, and YouTube facilitate knowledge exchange among farmers, researchers, and extension professionals through expert interactions, educational videos, and online discussions (Mahalakshmi *et al.*, 2014; FAO, 2022).

Artificial Intelligence (AI)-Based Advisory Systems

AI-based technologies are emerging as powerful tools for aquaculture management. These systems can assist in disease identification, image-based diagnosis, predictive analysis, and providing farm-specific recommendations for improved decision-making (Cui *et al.*, 2025; ICAR, 2024).

Internet of Things (IoT)

IoT-based systems use sensors and connected devices to monitor real-time water quality parameters such as temperature, dissolved oxygen, pH, and ammonia. Continuous monitoring helps farmers maintain suitable culture conditions and improve production efficiency (ICAR, 2024; Cui *et al.*, 2025).

Remote Sensing and Geographic Information Systems (GIS)

Remote sensing and GIS technologies support aquaculture planning by assessing suitable culture areas, monitoring environmental changes, and assisting resource management decisions for sustainable development (FAO, 2022).

Cloud-Based Farm Management Systems

Cloud-based platforms enable digital recording and analysis of farm activities, including stocking, feeding, water quality, growth performance, and harvesting. These systems support data-driven farm management and improved decision-making (Mathisen *et al.*, 2016).

Digital Marketing and E-Commerce Platforms

Digital marketplaces improve connectivity between fish farmers, buyers, and consumers by providing market information, improving price transparency, and expanding marketing opportunities (FAO, 2022). The integration of these technologies is making aquaculture more efficient, knowledge-based, and sustainable. With increasing digital connectivity, digital extension services are expected to play a crucial role in enhancing productivity, profitability, and resilience of the aquaculture sector (FAO, 2022; Byamukama *et al.*, 2025).

Types of Information Delivered to Fish Farmers

Digital extension services provide fish farmers with a wide range of scientific and practical information that supports efficient farm management throughout the production cycle. By delivering timely and location-specific advisories, these services help farmers make informed decisions, improve productivity, and minimize production risks (FAO, 2022; ICAR-CIFA, 2023).

Pond Preparation and Stocking

Digital platforms provide step-by-step guidance on pond preparation, including pond drying, liming, fertilization, and water filling. Farmers also receive recommendations on selecting healthy fish seed, maintaining appropriate stocking density, and adopting suitable culture practices for different fish species (ICAR-CIFA, 2023; FAO, 2022).

Water Quality Management

Maintaining good water quality is essential for healthy fish growth. Digital advisory services provide information on monitoring important water quality parameters such as temperature, pH, dissolved oxygen, ammonia, alkalinity, and transparency. Farmers also receive recommendations for correcting water quality problems before they affect fish health (Boyd & Tucker, 2012; ICAR-CIFA, 2023).

Feeding and Nutrition

Proper feeding is one of the most important factors influencing fish growth and profitability. Digital platforms offer guidance on feed type, feeding frequency, ration size, and nutritional requirements for different growth stages. Some advanced systems also recommend feeding schedules based on fish biomass and environmental conditions, helping to reduce feed wastage and production costs (FAO, 2022; ICAR-CIFE, 2023).

Fish Health and Disease Management

One of the most valuable features of digital extension is timely disease advisory. Farmers can access information on common fish diseases, recognize early clinical signs, upload photographs of diseased fish for expert consultation, and receive recommendations on preventive measures and appropriate treatment. Early diagnosis helps reduce mortality and improves farm productivity (WOAH, 2023; ICAR-CIFA, 2023).

Weather and Climate Advisories

Weather plays a significant role in aquaculture production. Digital services provide real-time weather forecasts, rainfall predictions, temperature alerts, and warnings about extreme weather events such as floods, cyclones, or heatwaves. These advisories help farmers take preventive measures to protect their fish stocks and infrastructure (FAO, 2022).

Market Information

Digital platforms provide up-to-date information on fish prices, market demand, buyer contacts, and marketing opportunities. Access to current market information enables farmers to plan harvesting and sales more effectively, improving profitability and reducing dependence on intermediaries (FAO, 2022).

Government Schemes and Financial Services

Fish farmers receive regular updates on government programmes, subsidies, insurance schemes, credit facilities, and training opportunities offered by fisheries departments and financial institutions. Easy access to such information encourages greater participation in development programmes and supports farm expansion (Department of Fisheries, Government of India, 2023).

Training and Capacity Building

Digital extension platforms offer educational resources such as videos, webinars, online training programmes, digital manuals, and interactive learning modules. These resources help farmers continuously upgrade their technical knowledge, learn about emerging technologies, and adopt improved aquaculture practices (ICAR-CIFE, 2023; Mahalakshmi *et al.*, 2014).

Overall, digital extension services act as a comprehensive knowledge hub by delivering accurate, timely, and practical information directly to fish farmers. Easy access to scientific advisory services enables farmers to improve management practices, reduce production risks, enhance fish health, and achieve sustainable aquaculture development (FAO, 2022; Byamukama *et al.*, 2025).

Successful Digital Initiatives in Fisheries

Several digital initiatives have been introduced in India to strengthen fisheries extension services and improve access to scientific information, government support, and market opportunities. These initiatives are helping fish farmers adopt modern aquaculture practices, improve productivity, and make informed management decisions (Department of Fisheries, 2020; FAO, 2022).

Pradhan Mantri Matsya Sampada Yojana (PMMSY)

The Pradhan Mantri Matsya Sampada Yojana (PMMSY), launched by the Department of Fisheries, Government of India, promotes the modernization of the fisheries sector through digital governance and technology-driven extension services. Online application systems, beneficiary tracking, digital monitoring, and electronic information dissemination have improved transparency and enabled farmers to access subsidies, infrastructure support, training programmes, and financial assistance more efficiently (Department of Fisheries, 2020).

National Fisheries Digital Platform (NFDP)

The National Fisheries Digital Platform (NFDP) is a digital ecosystem developed to integrate fisheries-related information and services on a single platform. It facilitates farmer registration, digital records, advisory services, scheme implementation, and linkages among fish farmers, researchers, financial institutions, and government agencies. The platform is expected to improve transparency, data management, and service delivery across the fisheries sector (Department of Fisheries, 2024).

ICAR–Central Institute of Freshwater Aquaculture (ICAR-CIFA)

ICAR–CIFA provides scientific advisory services through its official website, extension publications, training programmes, webinars, mobile-based communication, and social media platforms. Farmers receive guidance on freshwater aquaculture, pond management, fish breeding, nutrition, water quality, and disease management based on current scientific research (ICAR-CIFA, 2023).

ICAR–Central Institute of Fisheries Education (ICAR-CIFE)

ICAR–CIFE conducts online training programmes, webinars, digital learning modules, and outreach activities to enhance the technical knowledge of fish farmers, students, entrepreneurs, and fisheries professionals. These initiatives promote skill development and encourage the adoption of improved aquaculture technologies (ICAR-CIFE, 2023).

mKisan Advisory Services

The Government of India's mKisan portal enables experts to send SMS-based advisories to farmers in regional languages. Fisheries-related messages include recommendations on pond management, weather forecasts, disease prevention, and government programmes. The platform has significantly improved the dissemination of timely information, particularly in rural areas with limited internet access (Ministry of Agriculture & Farmers Welfare, 2023).

State Fisheries Department Digital Services

Several State Fisheries Departments have developed online portals and mobile-based services that provide information on fish seed availability, licensing, subsidy applications, training programmes, weather advisories, and disease management. These services improve communication between fisheries departments and farmers while increasing the efficiency of extension activities (Department of Fisheries, 2020).

Social Media-Based Knowledge Sharing

Digital communication platforms such as YouTube, WhatsApp, Facebook, and Telegram are increasingly used by ICAR institutes, Krishi Vigyan Kendras (KVKs), fisheries universities, and State Fisheries Departments to share technical videos, demonstration programmes, extension bulletins, and live interactions with experts. These platforms facilitate rapid knowledge exchange and encourage peer-to-peer learning among fish farmers (FAO, 2022; Mahalakshmi *et al.*, 2014). The

growing adoption of these digital initiatives demonstrates India's commitment to strengthening fisheries extension through modern information technologies. By integrating scientific research with digital communication tools, these initiatives are improving information accessibility, enhancing farmers' decision-making capacity, and supporting sustainable aquaculture development (FAO, 2022; Department of Fisheries, 2024).

Challenges in Digital Extension Services

Despite the increasing adoption of digital technologies in aquaculture, several challenges hinder the effective implementation of digital extension services. Addressing these limitations is essential to ensure equitable access to reliable advisory services for fish farmers across diverse production systems (FAO, 2022; Byamukama *et al.*, 2025).

Limited Internet Connectivity

Poor internet connectivity in rural and remote aquaculture regions restricts farmers' access to real-time advisories, online training, and digital extension platforms (FAO, 2022).

Digital Literacy

Limited digital skills, particularly among small-scale and elderly farmers, reduce the effective use of smartphones, mobile applications, and online advisory services. Regular digital literacy and capacity-building programmes are therefore essential (Byamukama *et al.*, 2025).

Language and Communication Barriers

Many digital platforms provide information only in English or a few regional languages, limiting their accessibility. User-friendly, multilingual advisory systems are needed to improve outreach and adoption (FAO, 2022).

Limited Access to Digital Devices

The high cost of smartphones, computers, and internet services remains a major constraint for resource-poor fish farmers, restricting their participation in digital extension programmes (FAO, 2022).

Quality and Reliability of Information

The widespread availability of unverified online information may lead to inappropriate farm management decisions. Farmers should rely on advisories provided by recognized institutions such as fisheries departments, ICAR institutes, universities, and international organizations (FAO, 2022; ICAR-CIFA, 2023).

Data Privacy and Cybersecurity

Digital advisory platforms collect farm and user information, making data security and privacy essential for maintaining user confidence and ensuring responsible data management (FAO, 2022).

Limited Technical Support

Digital technologies complement but cannot replace field-based extension services. Personalized expert support remains necessary for complex issues such as disease diagnosis, water quality management, and emergency response (Kumaran *et al.*, 2011).

Infrastructure and Financial Constraints

The expansion of digital extension depends on reliable electricity, internet infrastructure, technical expertise, and adequate financial investment. Inadequate infrastructure continues to limit digital transformation in many developing regions (FAO, 2022; Byamukama *et al.*, 2025). Overcoming

these challenges through improved digital infrastructure, enhanced digital literacy, multilingual platforms, and stronger integration of digital and conventional extension systems will maximize the impact of digital extension services and promote sustainable aquaculture development (FAO, 2022; Byamukama *et al.*, 2025).

Future Prospects

The future of digital extension in aquaculture will be driven by emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), big data analytics, blockchain, cloud computing, and remote sensing. These innovations are expected to improve farm management, enhance resource-use efficiency, strengthen disease surveillance, and support precision aquaculture. AI-based advisory systems will facilitate rapid disease diagnosis and decision-making, while IoT-enabled sensors will provide real-time monitoring of critical water quality parameters. Big data analytics and blockchain technology will further improve farm planning, traceability, and supply chain transparency, whereas digital marketplaces and e-learning platforms will enhance market access and farmers' technical capacity. Continued investment in digital infrastructure, internet connectivity, and collaborative efforts among research institutions, government agencies, and the private sector will accelerate the adoption of digital extension services. Rather than replacing conventional extension, digital technologies will complement existing systems to promote efficient, resilient, and sustainable aquaculture.

Conclusion

Digital extension services are transforming aquaculture by providing fish farmers with timely, reliable, and science-based advisory support through ICT-enabled platforms. Improved access to information on water quality, nutrition, disease management, weather, markets, and government programmes enables informed decision-making, enhances productivity, and reduces production risks. Although challenges related to connectivity, digital literacy, and infrastructure remain, ongoing technological advancements and supportive policies are accelerating digital transformation in the fisheries sector. Integrating digital tools with conventional extension systems will strengthen knowledge transfer, improve farm profitability, and promote sustainable and climate-resilient aquaculture, ultimately contributing to food security and rural livelihoods.

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ROLE OF FISHERIES EXTENSION IN SUSTAINABLE AQUACULTURE: BRIDGING SCIENCE AND FISH FARMERS

Ankit Yadav* and Anupam Anand

College of Fisheries Science, Hisar, CCSHAU, Haryana-125004

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Aquaculture is one of the fastest-growing food production sectors worldwide and plays a crucial role in ensuring food security, nutritional security, employment generation, and economic development. However, rapid expansion of aquaculture has also created challenges such as disease outbreaks, environmental degradation, climate change, and inefficient resource utilization. Sustainable aquaculture aims to increase fish production while conserving aquatic ecosystems and natural resources. Fisheries extension plays a pivotal role in achieving this goal by acting as a bridge between research institutions and fish farmers. It facilitates the transfer of scientific knowledge, innovative technologies, and best management practices through training programmes, demonstrations, advisory services, and digital communication platforms. Fisheries extension also promotes climate-smart aquaculture, fish health management, environmental conservation, and market-oriented production systems. The integration of digital technologies, including mobile applications, Artificial Intelligence (AI), the Internet of Things (IoT), and online advisory services, has further strengthened extension systems by providing real-time technical support to farmers. This article highlights the concept of fisheries extension, its major roles in promoting sustainable aquaculture, modern extension approaches, and its contribution to improving farmers' livelihoods while ensuring environmental sustainability.

Keywords: Fisheries Extension, Sustainable Aquaculture, Technology Transfer, Fish Farmers, Digital Extension, Climate-Smart Aquaculture.

Introduction

Aquaculture has become one of the most dynamic food production sectors in the world and is recognized as an important contributor to food security, nutrition, employment, and economic growth (FAO, 2024). With declining capture fisheries and increasing global demand for aquatic foods, aquaculture has emerged as a sustainable solution for meeting future food requirements. According to the Food and Agriculture Organization (FAO), aquaculture currently contributes more than half of the aquatic animals produced for human consumption worldwide (FAO, 2024). India is the second-largest fish-producing country globally, with fisheries and aquaculture contributing significantly to agricultural GDP, export earnings, and rural livelihoods (ICAR, 2023). The sector provides direct and indirect employment to millions of people, particularly in rural and coastal areas. Freshwater aquaculture, brackish-water farming, cage culture, biofloc technology, recirculating aquaculture systems (RAS), and integrated fish farming have expanded rapidly over the past decade, creating new opportunities for income generation and entrepreneurship (FAO, 2022). Despite these achievements, the aquaculture sector faces several challenges, including disease outbreaks, poor water quality, rising feed costs, indiscriminate use of antibiotics, environmental pollution, and climate change (Boyd & McNevin, 2021). These challenges reduce productivity, increase production costs, and threaten the long-term sustainability of aquaculture.

Many fish farmers, particularly small-scale producers, continue to depend on traditional farming practices because of limited access to scientific information, modern technologies, and professional advisory services (Nabi *et al.*, 2025).

Sustainable aquaculture emphasizes fish production through environmentally responsible, economically viable, and socially acceptable farming practices. It focuses on efficient resource utilization, ecosystem conservation, responsible input use, improved fish health management, and enhanced farm profitability (FAO, 2022). Achieving these objectives requires continuous education, technical support, and effective communication between scientists and fish farmers. Fisheries extension serves as the vital link connecting research institutions, universities, government organizations, and farming communities. It ensures that scientific innovations developed in laboratories reach farmers in a practical and understandable form. Through training programmes, field demonstrations, farmer-scientist interactions, exposure visits, and digital advisory services, fisheries extension promotes the adoption of improved technologies and sustainable farming practices (ICAR, 2023; Rowan, 2023). Consequently, it enhances fish production, improves farmers' income, strengthens resilience to climate change, and contributes to the sustainable development of the aquaculture sector.

Concept of Fisheries Extension

Fisheries extension is an educational and communication process through which scientific knowledge, innovative technologies, and improved aquaculture practices are transferred from research institutions to fish farmers (Nabi *et al.*, 2025). It aims to improve farmers' knowledge, technical skills, and decision-making capacity, enabling them to adopt sustainable production practices and increase farm profitability. Unlike conventional information dissemination, fisheries extension is a two-way communication process. Extension personnel not only provide technical recommendations but also identify farmers' problems, understand local conditions, collect feedback, and communicate farmers' needs to researchers. This participatory approach facilitates the development and dissemination of technologies that are practical, location-specific, and farmer-friendly (ICAR, 2023). The major objectives of fisheries extension include:

- Dissemination of scientific aquaculture technologies.
- Capacity building through training and demonstrations.
- Promotion of sustainable and climate-resilient aquaculture.
- Fish health and biosecurity management.
- Efficient utilization of water, feed, and other resources.
- Market linkage and value addition.
- Improvement of farmers' income and livelihood security.

Therefore, fisheries extension functions as a bridge between scientific research and practical aquaculture by transforming research outputs into field-level applications (FAO, 2022).

Role of Fisheries Extension in Sustainable Aquaculture

Technology Transfer and Adoption of Improved Farming Practices

Technology transfer is one of the fundamental responsibilities of fisheries extension. Scientific research continuously generates improved technologies for fish seed production, pond management, nutrition, disease control, water quality management, and harvesting. However, these innovations benefit farmers only when they are effectively communicated and adopted at the field level (FAO, 2022). Extension personnel organize demonstrations, field visits, farmer

training programmes, and awareness campaigns to encourage the adoption of improved technologies. Farmers receive guidance on scientific pond preparation, water quality management, optimum stocking density, quality seed selection, balanced feeding, aeration, health monitoring, and record keeping. They are also introduced to advanced production systems such as biofloc technology, recirculating aquaculture systems (RAS), aquaponics, cage culture, and integrated fish farming (ICAR, 2023). The adoption of these technologies improves feed conversion efficiency, enhances fish growth and survival, reduces production costs, and minimizes environmental impacts (Boyd & McNevin, 2021). Scientific record-keeping and farm monitoring further support informed decision-making, leading to higher productivity and long-term sustainability.

Capacity Building and Farmer Education

Knowledge and technical skills are essential for sustainable aquaculture development. Fisheries extension strengthens farmers' capacity through training programmes, workshops, field demonstrations, farmer field schools, exposure visits, and practical learning sessions (Nabi *et al.*, 2025). These educational activities help farmers understand scientific principles and apply them under local farming conditions. Training programmes cover pond preparation, hatchery management, nursery rearing, feed formulation, water quality monitoring, disease diagnosis, biosecurity, harvesting techniques, post-harvest management, and farm economics. Extension agencies also prepare educational materials such as manuals, leaflets, videos, and digital learning resources in local languages to improve accessibility (ICAR, 2023). Continuous learning enables farmers to solve production problems scientifically, adopt innovative technologies, reduce production risks, and improve farm profitability. Capacity-building programmes also encourage youth and women to participate in fisheries and aquaculture enterprises, thereby creating employment opportunities and promoting inclusive rural development (FAO, 2024).

Fish Health Management and Biosecurity

Disease outbreaks remain one of the major constraints affecting aquaculture production worldwide. Bacterial, viral, fungal, and parasitic diseases often cause significant economic losses due to increased mortality, reduced growth, and poor product quality (FAO, 2022). Fisheries extension plays a crucial role in promoting preventive fish health management through farmer education and technical guidance. Extension personnel educate farmers about maintaining optimum water quality, selecting disease-free seed, implementing appropriate stocking densities, and providing nutritionally balanced feed. Farmers are trained to recognize early clinical signs of diseases, monitor fish behaviour, and seek laboratory diagnosis before disease outbreaks become severe (Nabi *et al.*, 2025). Biosecurity measures such as pond disinfection, equipment sanitation, quarantine of newly introduced fish, restricted farm access, and safe disposal of dead fish are strongly emphasized. Extension services also promote the responsible use of antibiotics, probiotics, immunostimulants, and herbal health management practices to reduce antimicrobial resistance and environmental contamination (Boyd & McNevin, 2021). Preventive health management significantly improves fish survival, reduces treatment costs, and enhances farm sustainability.

Water Quality Management and Resource Efficiency

Water quality is one of the most critical factors influencing fish health and aquaculture productivity. Fisheries extension provides scientific guidance on monitoring important water quality parameters such as temperature, pH, dissolved oxygen, ammonia, alkalinity, hardness, and

transparency (Boyd & McNevin, 2021). Farmers are encouraged to conduct regular water quality assessments and adopt corrective measures whenever required. Extension personnel also promote efficient feed management to reduce feed wastage and nutrient loading in ponds. Scientific recommendations on feeding frequency, ration size, and feed quality improve feed conversion ratio (FCR), reduce production costs, and minimize environmental pollution (FAO, 2022). Proper pond preparation, liming, fertilization, aeration, sludge management, and routine water quality monitoring further improve resource-use efficiency and support sustainable aquaculture production systems (ICAR, 2023).

Environmental Sustainability

Environmental sustainability is a fundamental principle of responsible aquaculture, ensuring that fish production is achieved without compromising aquatic ecosystems or natural resources (FAO, 2022). Fisheries extension plays a crucial role in promoting environmentally sound farming practices by educating farmers on sustainable resource management and responsible aquaculture techniques. Poor farm management, excessive feed application, overstocking, and indiscriminate use of chemicals can deteriorate water quality, increase disease incidence, and pollute surrounding aquatic environments (Boyd & McNevin, 2021). Extension personnel therefore provide technical guidance on scientific pond preparation, optimum stocking density, efficient feed utilization, regular monitoring of water quality parameters, and proper waste management to minimize environmental degradation. In addition, fisheries extension promotes environmentally sustainable production systems such as biofloc technology, integrated fish farming, aquaponics, and recirculating aquaculture systems (RAS), which improve water-use efficiency, reduce waste generation, and enhance resource utilization (Edwards, 2020; FAO, 2024). Farmers are also encouraged to conserve aquatic biodiversity, prevent the discharge of untreated pond effluents into natural water bodies, and adopt responsible aquaculture practices that ensure long-term productivity while maintaining ecological balance.

Climate-Smart Aquaculture

Climate change has emerged as one of the greatest challenges to sustainable aquaculture, affecting water availability, temperature, dissolved oxygen levels, disease outbreaks, and fish productivity (FAO, 2024). Extreme weather events such as floods, droughts, and irregular rainfall further increase production risks and economic losses for fish farmers (United Nations, 2023). Fisheries extension helps farmers understand these challenges and promotes climate-smart aquaculture practices that enhance resilience and sustainability. Extension professionals provide timely advisories on weather forecasting, water conservation, emergency aeration, pond management during extreme climatic conditions, and the selection of climate-resilient fish species. Farmers are also encouraged to diversify production systems, integrate aquaculture with agriculture, adopt rainwater harvesting, and improve resource-use efficiency to minimize climate-related risks (FAO, 2022; Nabi *et al.*, 2025). Through continuous education and technical support, fisheries extension strengthens farmers' adaptive capacity and contributes to resilient and sustainable aquaculture systems.

Digital Fisheries Extension

Advances in Information and Communication Technologies (ICTs) have transformed the delivery of fisheries extension services by improving the accessibility, speed, and efficiency of scientific information (Rowan, 2023). Digital platforms such as mobile applications, social media, WhatsApp groups, webinars, online training programmes, and SMS-based advisory services enable farmers to

receive real-time recommendations on fish farming practices, disease management, water quality, and market information. Emerging technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, drones, cloud computing, and decision-support systems, are further revolutionizing aquaculture management (WorldFish, 2023). AI-assisted disease diagnosis, sensor-based water quality monitoring, automated feeding systems, and digital farm advisory services improve management decisions, optimize resource utilization, and reduce production costs. Digital fisheries extension also strengthens communication among researchers, extension professionals, and fish farmers, accelerating technology transfer and supporting the adoption of precision aquaculture for sustainable production (Rowan, 2023).

Challenges in Fisheries Extension

Despite its significant contribution to aquaculture development, fisheries extension faces several challenges that limit its effectiveness. Many developing countries experience shortages of trained extension professionals, inadequate infrastructure, and limited financial resources for field-level advisory services (FAO, 2022). Small-scale fish farmers often have restricted access to quality seed, scientific information, modern technologies, institutional credit, and organized markets, which hinders the adoption of improved aquaculture practices. The digital divide, poor internet connectivity, low digital literacy, language barriers, and weak market linkages further reduce the effectiveness of extension programmes (Rowan, 2023). Additionally, emerging fish diseases, increasing production costs, environmental degradation, and climate change require continuous technical support and rapid dissemination of scientific innovations. Strengthening institutional collaboration, enhancing digital infrastructure, increasing investment in extension services, and promoting farmer participation are therefore essential for improving the effectiveness of fisheries extension.

Future Prospects

The future of fisheries extension will depend on the effective integration of modern digital technologies with participatory and climate-resilient extension approaches. Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), blockchain technology, satellite-based monitoring, and precision aquaculture are expected to improve farm management, resource efficiency, and decision-making (WorldFish, 2023). Smart sensors for continuous water quality monitoring and AI-powered disease diagnostic tools will enable early detection of health problems and timely management interventions. Future extension programmes should also emphasize sustainable intensification, biosecurity, environmental conservation, responsible resource utilization, women's empowerment, youth entrepreneurship, and Farmer Producer Organizations (FPOs) to strengthen the aquaculture value chain (FAO, 2024; ICAR, 2023). Greater collaboration among research institutions, universities, government agencies, private organizations, and farming communities will facilitate faster technology adoption and enhance the sustainability of aquaculture.

Table 1. Major roles of fisheries extension in promoting sustainable aquaculture through technology dissemination, capacity building, environmental management, and digital innovations.

Extension Component	Major Activities	Contribution to Sustainable Aquaculture
Technology Transfer	Dissemination of improved farming technologies, demonstrations, farmer training	Enhances productivity, feed efficiency, and adoption of scientific aquaculture practices

Extension Component	Major Activities	Contribution to Sustainable Aquaculture
Capacity Building	Workshops, field schools, exposure visits, skill development programmes	Improves farmers' knowledge, technical skills, and decision-making capacity
Fish Health and Biosecurity	Disease surveillance, health advisory, biosecurity awareness, responsible antibiotic use	Reduces disease outbreaks, improves fish survival, and promotes responsible health management
Water Quality Management	Monitoring of water quality parameters, feed management, pond management	Maintains optimal culture conditions, improves growth, and minimizes environmental pollution
Environmental Sustainability	Promotion of eco-friendly farming systems, waste management, biodiversity conservation	Protects aquatic ecosystems and ensures long-term sustainability
Climate-Smart Aquaculture	Climate advisory services, water conservation, resilient farming practices	Enhances resilience against climate change and reduces production risks
Digital Fisheries Extension	Mobile applications, AI, IoT, online training, digital advisory services	Enables real-time decision-making, rapid information dissemination, and precision aquaculture
Marketing and Livelihood Support	Market linkage, value addition, financial guidance, entrepreneurship development	Improves farmers' income, market access, and livelihood security

Conclusion

Fisheries extension is a cornerstone of sustainable aquaculture because it bridges the gap between scientific research and practical farming. Through technology transfer, farmer education, fish health management, environmental conservation, climate adaptation, and digital innovation, extension services significantly improve aquaculture productivity, profitability, and sustainability (FAO, 2022). The integration of advanced digital technologies with farmer-centred extension programmes will further strengthen sustainable aquaculture by improving resource-use efficiency, enhancing climate resilience, and promoting environmentally responsible farming practices. Continued investment in fisheries extension, capacity building, research–extension–farmer linkages, and digital advisory systems will be essential for ensuring food security, improving rural livelihoods, and achieving the long-term sustainable development of the aquaculture sector.

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**MOBILE APPS AND ICT TOOLS FOR FISH FARMERS:
TRANSFORMING AQUACULTURE THROUGH DIGITAL INNOVATION****Ankit Yadav* and Anupam Anand**

College of Fisheries Science, Hisar, CCSHAU, Haryana-125004

Corresponding Email: vijaychaudhary30358@gmail.com**Abstract**

Aquaculture has become one of the fastest-growing food production sectors globally, contributing significantly to food security, nutrition, employment, and economic development. However, fish farmers continue to face challenges such as disease outbreaks, poor water quality, fluctuating market prices, climate variability, and limited access to technical information. Information and Communication Technologies (ICTs), particularly mobile applications, have emerged as effective tools for addressing these challenges by providing real-time advisory services and facilitating informed decision-making. Mobile apps, artificial intelligence (AI), Internet of Things (IoT), remote sensing, cloud computing, and social media platforms have revolutionized fisheries extension by improving communication between researchers, extension personnel, and farmers. These technologies enable continuous monitoring of water quality, disease diagnosis, feed management, weather forecasting, and market information, thereby enhancing farm productivity and sustainability. This article discusses the role of mobile applications and ICT tools in modern aquaculture, their applications, benefits, and contribution to sustainable fish farming.

Keywords: Aquaculture, ICT, Mobile Applications, Digital Extension, Artificial Intelligence, Internet of Things, Sustainable Fish Farming.

Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors in the world, supplying more than half of the aquatic animals consumed globally and contributing significantly to food security, nutrition, employment, and economic development (FAO, 2024). In India, fisheries and aquaculture play an important role in rural livelihoods and income generation, making the country the second-largest producer of fish worldwide (ICAR, 2023). However, sustainable aquaculture is increasingly challenged by disease outbreaks, poor water quality, climate change, increasing feed costs, and limited access to scientific information, particularly among small-scale fish farmers (FAO, 2022). Traditionally, fish farmers depended on extension officers, printed manuals, and occasional training programmes for technical guidance. Although these methods remain important, they often fail to provide timely solutions to rapidly changing farm conditions. The widespread availability of smartphones, affordable internet services, and digital communication technologies has transformed the way information is delivered to farmers. Mobile applications and other Information and Communication Technologies (ICTs) now enable farmers to access scientific recommendations, weather forecasts, disease alerts, market prices, and management advisories instantly (Rowan, 2023). The Government of India has also promoted digital agriculture through initiatives such as Digital India, e-Governance, and mobile-based extension services, encouraging the adoption of ICT tools in fisheries and aquaculture. These digital technologies not only improve communication between researchers, extension personnel, and farmers but also support precision aquaculture by enabling data-driven farm management

(WorldFish, 2023). Consequently, ICT-based advisory systems are becoming indispensable for achieving sustainable, profitable, and climate-resilient aquaculture.

Information and Communication Technologies (ICTs) in Fisheries

Information and Communication Technologies (ICTs) refer to digital tools and communication systems used for collecting, processing, storing, and disseminating information. In fisheries and aquaculture, ICTs facilitate the rapid transfer of scientific knowledge, improve access to advisory services, and strengthen communication among researchers, extension professionals, policymakers, and fish farmers (FAO, 2022).

ICT-based extension includes mobile applications, SMS services, websites, social media platforms, cloud-based information systems, artificial intelligence (AI), Internet of Things (IoT), remote sensing, Geographic Information Systems (GIS), drones, and digital decision-support systems. These technologies allow farmers to obtain real-time technical guidance without depending solely on physical visits by extension personnel. Modern ICT tools support evidence-based decision-making by providing location-specific recommendations on pond preparation, water quality management, feeding schedules, disease diagnosis, harvesting, weather forecasting, and market prices. They also improve information sharing among farming communities, encourage knowledge exchange, and facilitate rapid dissemination of research findings (WorldFish, 2023). Consequently, ICTs have become an integral component of digital fisheries extension and sustainable aquaculture development.

Role of Mobile Applications in Fish Farming

Mobile applications have emerged as one of the most accessible and effective ICT tools for fish farmers. With increasing smartphone penetration in rural areas, mobile apps provide farmers with scientific information anytime and anywhere, reducing their dependence on conventional extension services. These applications integrate multiple advisory functions into a single digital platform, making farm management more efficient and data-driven (Rowan, 2023). Several fisheries mobile applications provide guidance on pond preparation, species selection, stocking density, feed management, water quality monitoring, disease identification, medicine recommendations, weather forecasting, and market information. Farmers can also upload photographs of diseased fish for preliminary diagnosis, receive expert recommendations, maintain digital farm records, and monitor production performance. Such applications improve farm management efficiency, reduce operational costs, and enhance productivity (FAO, 2024). Mobile apps also strengthen communication between fish farmers, scientists, veterinarians, and fisheries extension officers through chat services, video consultations, and online advisory platforms. Instant access to technical expertise enables farmers to make timely management decisions and respond quickly to disease outbreaks or adverse environmental conditions.

Mobile Applications for Water Quality Management

Water quality is one of the most important determinants of fish health and production. Regular monitoring of physicochemical parameters such as temperature, pH, dissolved oxygen, ammonia, alkalinity, salinity, and turbidity is essential for maintaining a healthy aquatic environment (Boyd & McNevin, 2021). Mobile applications integrated with digital sensors and IoT devices allow farmers to monitor these parameters in real time and receive alerts whenever values exceed optimum limits. Several applications also provide recommendations for corrective measures such as water exchange, liming, aeration, or feed adjustment based on water quality data. Continuous

monitoring helps prevent stress, reduce disease incidence, improve feed conversion efficiency, and enhance fish survival. By supporting data-driven management, mobile applications contribute significantly to sustainable aquaculture and efficient resource utilization.

Mobile Applications for Feed Management

Feed accounts for approximately 50–70% of total aquaculture production costs, making efficient feed management essential for profitable fish farming (FAO, 2022). Mobile applications assist farmers in calculating daily feed requirements based on fish species, biomass, stocking density, water temperature, and growth stage. Advanced applications maintain digital feeding records, estimate Feed Conversion Ratio (FCR), remind farmers about feeding schedules, and recommend appropriate feed quantities according to production targets. Some AI-enabled applications also analyse feeding behaviour and optimize feeding frequency, thereby minimizing feed wastage and reducing environmental pollution. Improved feed management not only lowers production costs but also enhances fish growth and overall farm profitability.

Mobile Applications for Disease Diagnosis and Fish Health Management

Disease outbreaks remain one of the major constraints in aquaculture, causing substantial economic losses worldwide. Early detection and rapid intervention are essential for effective disease control. Mobile applications equipped with image recognition and Artificial Intelligence (AI) technologies can assist farmers in identifying common bacterial, viral, fungal, and parasitic diseases based on clinical signs and lesion photographs (WorldFish, 2023). Many applications also provide information on disease symptoms, preventive biosecurity measures, treatment protocols, and responsible use of therapeutics. Farmers can consult fisheries experts through online advisory platforms and receive immediate technical support without travelling to diagnostic laboratories. These digital tools facilitate early disease reporting, improve biosecurity, reduce production losses, and promote responsible fish health management while minimizing the indiscriminate use of antibiotics (FAO, 2024).

Mobile Applications for Weather Forecasting and Market Information

Weather variability significantly influences aquaculture production by affecting water temperature, dissolved oxygen concentration, rainfall, and disease occurrence. Mobile applications integrated with meteorological data provide real-time weather forecasts, rainfall predictions, cyclone alerts, and temperature updates, enabling farmers to undertake preventive measures such as aeration, water exchange, and harvest planning (FAO, 2024). Early weather warnings reduce production risks and enhance farm resilience under changing climatic conditions. In addition to weather information, mobile applications provide access to current fish market prices, demand trends, input availability, and marketing opportunities. Farmers can compare prices across different markets, identify profitable selling periods, and establish direct communication with buyers, thereby reducing the role of intermediaries and improving farm income (ICAR, 2023).

Emerging ICT Tools in Aquaculture

Artificial Intelligence (AI)

Artificial Intelligence (AI) is transforming aquaculture by enabling data-driven decision-making and precision farming. AI algorithms analyze large datasets generated from fish farms to predict disease outbreaks, estimate growth performance, optimize feeding schedules, and improve water quality management (WorldFish, 2023). Image-based AI systems can identify disease symptoms

from photographs of infected fish and provide preliminary diagnostic recommendations, allowing timely intervention and reducing economic losses. AI also supports automated decision-making, thereby improving production efficiency and sustainability (FAO, 2024).

Internet of Things (IoT)

The Internet of Things (IoT) refers to interconnected sensors and smart devices that continuously monitor environmental parameters. In aquaculture, IoT-based sensors measure water temperature, pH, dissolved oxygen, ammonia, salinity, and turbidity in real time. These sensors automatically transmit data to mobile applications or cloud platforms, allowing farmers to monitor pond conditions remotely (Boyd & McNevin, 2021). Automated aerators and feeders linked with IoT systems further enhance farm efficiency by reducing labour requirements and optimizing resource utilization.

Geographic Information System (GIS) and Remote Sensing

GIS and remote sensing technologies assist in aquaculture planning, site selection, environmental monitoring, and resource management. Satellite imagery and spatial analysis help identify suitable farming locations based on water availability, land use, soil characteristics, and climatic conditions (FAO, 2022). These technologies also support monitoring of water bodies, flood-prone areas, and environmental changes, thereby improving long-term farm planning and sustainable resource management.

Drones and Cloud Computing

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are increasingly used for pond surveillance, infrastructure inspection, biomass estimation, and environmental monitoring. Drone imagery enables rapid assessment of pond conditions and early identification of management problems (WorldFish, 2023). Cloud computing further enhances digital aquaculture by securely storing farm records, production data, water quality information, and advisory services, allowing farmers and extension professionals to access information from any location.

Benefits of Mobile Apps and ICT Tools for Fish Farmers

The adoption of mobile applications and ICT tools has significantly improved aquaculture management by providing farmers with timely, accurate, and location-specific information. Real-time advisory services enhance decision-making, reduce production risks, and improve resource-use efficiency (Rowan, 2023). Digital technologies facilitate early disease detection, optimize feed management, improve water quality monitoring, and strengthen climate resilience. ICT tools also reduce farmers' dependence on conventional extension services by enabling direct communication with researchers and technical experts (Table 1). Digital record keeping improves farm planning, while online marketing platforms increase market access and profitability. Furthermore, ICT-based extension encourages knowledge sharing among farming communities and accelerates the adoption of innovative technologies, ultimately contributing to sustainable aquaculture development (FAO, 2024).

Table 1. Major ICT Tools and Their Applications in Aquaculture

ICT Tool	Primary Application	Benefits to Fish Farmers
Mobile Applications	Farm management, advisory services	Real-time technical guidance and improved decision-making
SMS and Mobile Alerts	Weather forecasts, disease alerts	Timely dissemination of critical information

ICT Tool	Primary Application	Benefits to Fish Farmers
Artificial Intelligence (AI)	Disease diagnosis, feeding optimization	Early disease detection and improved productivity
Internet of Things (IoT)	Water quality monitoring	Continuous monitoring and efficient resource management
GIS and Remote Sensing	Site selection and environmental monitoring	Better farm planning and climate adaptation
Drones (UAVs)	Pond inspection and surveillance	Rapid monitoring and reduced labour requirements
Cloud Computing	Digital record management	Secure data storage and easy information access
Social Media & WhatsApp	Farmer communication and knowledge sharing	Faster interaction with experts and extension personnel

Challenges in Adoption of ICT Tools

Despite their numerous advantages, several factors limit the widespread adoption of ICT tools among fish farmers. Limited digital literacy, inadequate internet connectivity, poor smartphone accessibility, language barriers, and lack of awareness remain major constraints, particularly in rural and remote areas (Rowan, 2023). Small-scale farmers may also face financial limitations in purchasing digital devices and IoT-based monitoring systems. Another challenge is the limited availability of region-specific mobile applications in local languages. In addition, concerns regarding data privacy, maintenance costs, and technical support may discourage farmers from adopting advanced digital technologies. Strengthening digital infrastructure, improving extension services, and providing regular capacity-building programmes are essential for overcoming these barriers.

Future Prospects

The future of fisheries extension will increasingly depend on the integration of advanced digital technologies with conventional advisory systems. Artificial Intelligence, Machine Learning, blockchain technology, IoT-enabled smart farms, cloud computing, and big data analytics are expected to transform aquaculture into a highly efficient and precision-based production system (WorldFish, 2023). Future mobile applications will likely provide automated disease diagnosis, predictive analytics, personalized farm advisory, multilingual voice-based assistance, and integration with government support programmes. Greater collaboration among research institutions, extension agencies, software developers, and fish farmers will accelerate technology adoption and improve the sustainability, profitability, and resilience of aquaculture (FAO, 2024).

Conclusion

Mobile applications and ICT tools have emerged as indispensable components of modern aquaculture by improving information access, strengthening fisheries extension, and supporting evidence-based farm management. These digital technologies enable farmers to monitor water quality, optimize feeding practices, diagnose diseases, access weather forecasts, and obtain market information in real time. Consequently, ICT-based advisory systems improve productivity, reduce production costs, enhance environmental sustainability, and strengthen climate resilience. Although challenges related to digital infrastructure, literacy, and accessibility remain, continued investment in digital extension, farmer training, and technology development will facilitate wider

adoption of ICT tools. Integrating mobile applications with Artificial Intelligence, IoT, remote sensing, and cloud-based platforms will further revolutionize aquaculture, contributing to sustainable fish production, improved farmer livelihoods, and long-term food security.

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CLIMATE-SMART TECHNOLOGIES FOR SUSTAINABLE AQUACULTURE

Krishna Karshan Bhai Chopara*

M.F.Sc. Student, Department of Aquaculture, College of Fisheries Science,
Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Climate change has emerged as one of the greatest challenges affecting global aquaculture, influencing the productivity, sustainability, and resilience of aquatic food production systems. Rising water temperatures, erratic rainfall, floods, droughts, sea-level rise, ocean acidification, and the increasing frequency of extreme weather events have significantly affected water quality, fish health, growth performance, reproduction, and farm infrastructure. These climate-related stresses increase disease outbreaks, reduce production efficiency, and threaten the livelihoods of millions of people who depend on aquaculture for food, income, and employment. As global demand for fish and other aquatic products continues to rise, there is an urgent need to adopt innovative farming approaches that can enhance productivity while minimizing environmental impacts and improving resilience to climate change. Climate-smart aquaculture (CSAq) has emerged as a sustainable approach that integrates advanced technologies, efficient resource management, and ecosystem-based practices to improve adaptation and mitigation in aquaculture. It focuses on increasing production and profitability while reducing greenhouse gas emissions, conserving water and energy resources, and enhancing the resilience of farming systems to climate variability.

Impacts of Climate Change on Aquaculture

Rising Water Temperatures

Increasing water temperatures significantly affect the physiology, metabolism, and productivity of cultured aquatic species. Elevated temperatures accelerate metabolic rates, increasing oxygen demand while simultaneously reducing dissolved oxygen concentrations in water, leading to hypoxic conditions. Prolonged thermal stress impairs growth, feed conversion efficiency, reproduction, and immune responses, making fish more susceptible to diseases. Marine heatwaves have become more frequent and intense, disrupting aquatic ecosystems, altering species distribution, and causing mass mortality events in both marine and freshwater aquaculture systems. These changes ultimately reduce production efficiency and economic returns.

Ocean Acidification

Ocean acidification results from the increased absorption of atmospheric carbon dioxide (CO₂), which lowers seawater pH and decreases carbonate ion availability. This process adversely affects calcifying organisms such as oysters, mussels, clams, and other shellfish by reducing shell formation, growth, and larval survival. Acidified conditions also impair reproduction, physiological functions, and stress tolerance, thereby decreasing aquaculture productivity. Long-term ocean acidification poses a serious challenge to sustainable shellfish farming and coastal aquaculture.

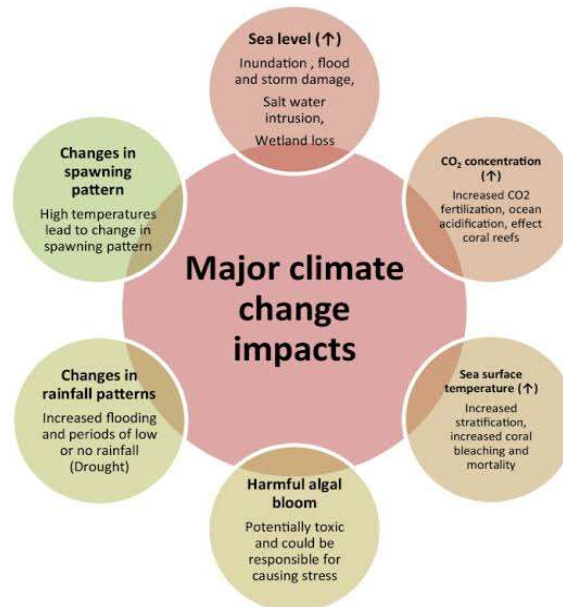


Figure 1. Major impacts of climate change on aquaculture production systems.

Salinity Intrusion

Climate change-induced sea-level rise, altered rainfall patterns, and reduced freshwater inflows have intensified salinity intrusion into coastal and inland water bodies. Fluctuating salinity levels disrupt osmoregulation, reduce feed intake, impair growth, and increase physiological stress in freshwater aquaculture species. Sensitive species may experience reduced survival and reproductive performance under prolonged saline conditions. Consequently, salinity intrusion decreases farm productivity and restricts species selection in affected regions.

Disease and Parasite Outbreaks

Rising water temperatures and environmental stress create favorable conditions for the proliferation of aquatic pathogens, parasites, and harmful microorganisms. Climate-induced stress weakens the immune system of cultured species, increasing their susceptibility to bacterial, viral, fungal, and parasitic infections. For example, warmer marine waters have promoted the spread of sea lice in salmon farming, resulting in significant production losses. Increased disease outbreaks elevate treatment costs, reduce survival rates, and threaten the sustainability of aquaculture operations.

Harmful Algal Blooms (HABs)

Climate change has increased the frequency, duration, and intensity of harmful algal blooms (HABs) in freshwater and marine environments. Elevated temperatures and nutrient enrichment stimulate the rapid growth of toxin-producing algae, leading to oxygen depletion, fish kills, and deterioration of water quality. HABs can contaminate cultured seafood with harmful toxins, posing risks to human health and causing severe economic losses. Effective monitoring and early warning systems are therefore essential for minimizing their impact on aquaculture.

Extreme Weather Events

The increasing occurrence of cyclones, floods, droughts, heatwaves, and storm surges poses significant risks to aquaculture production. These extreme weather events damage ponds, cages,

hatcheries, and supporting infrastructure, resulting in stock losses and interruptions in production cycles. Floods may introduce pollutants and pathogens, while droughts reduce water availability and deteriorate water quality. The growing frequency of such climate-related disasters increases operational costs, financial uncertainty, and the vulnerability of aquaculture-dependent communities.

Table 1. Climate Change Impacts and Climate-Smart Adaptation Strategies in Aquaculture

Climate Change Impact	Effect on Aquaculture	Climate-Smart Adaptation Strategy
Rising water temperature	Reduced growth, thermal stress	RAS, temperature monitoring, heat-tolerant species
Ocean acidification	Poor shell formation in shellfish	Water quality monitoring, selective breeding
Salinity intrusion	Osmotic stress and reduced survival	Salinity-tolerant species, water management
Disease outbreaks	Increased mortality and production losses	AI-based disease detection, biosecurity, vaccination
Harmful algal blooms	Fish mortality and poor water quality	Early warning systems, remote sensing
Extreme weather events	Infrastructure damage and stock losses	Climate-resilient infrastructure, insurance, disaster preparedness

Socio-Economic Implications

Climate change affects not only aquatic ecosystems but also the socio-economic well-being of communities dependent on aquaculture. Its major implications include:

- **Loss of livelihoods:** Climate-induced production losses, disease outbreaks, and extreme weather events reduce employment opportunities and income for fish farmers, hatchery operators, and other stakeholders.
- **Reduced income and increased production costs:** Farmers face higher expenses for feed, energy, disease management, water treatment, and infrastructure repair, while reduced production lowers profitability.
- **Threats to food and nutritional security:** Declining aquaculture productivity reduces the availability and affordability of fish, an important source of high-quality protein, essential fatty acids, vitamins, and minerals.

Aquaculture supports millions of livelihoods worldwide and contributes significantly to rural economies and global food systems. In countries such as India, climate change is increasingly affecting aquaculture-dependent communities by reducing production, increasing economic risks, and threatening long-term sustainability.

Innovative Approaches for Sustainable Aquaculture

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are advanced farming systems that continuously treat and reuse water through mechanical and biological filtration. These systems significantly reduce water consumption, improve water quality, and provide precise control over environmental conditions. RAS also enhances biosecurity by minimizing the risk of pathogen introduction and

reduces the impacts of climate variability, making aquaculture more sustainable and resource-efficient.

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) involves the co-culture of species from different trophic levels, such as finfish, shellfish, and seaweeds, within the same farming system. Waste nutrients released by one species are utilized by others, improving nutrient recycling and reducing environmental pollution. This integrated approach enhances resource efficiency, increases overall productivity, and promotes environmentally sustainable aquaculture.

Aquaponics Systems

Aquaponics combines aquaculture with hydroponic plant cultivation in a closed-loop production system. Fish waste provides nutrients for plant growth, while plants naturally filter and purify the water before it is recirculated back to the fish tanks. This system minimizes water use, reduces waste discharge, and enables the simultaneous production of fish and vegetables, making it a sustainable and climate-resilient farming practice.

Selective Breeding and Genetic Improvement

Selective breeding and modern genetic improvement techniques are used to develop aquaculture species with enhanced growth, disease resistance, feed efficiency, and tolerance to environmental stress. Climate-resilient strains capable of withstanding temperature fluctuations, salinity changes, and emerging diseases contribute to improved productivity and long-term sustainability under changing climatic conditions.

Digital Technologies and Artificial Intelligence

Digital technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), machine learning, and automated monitoring systems, are transforming aquaculture management. Smart sensors continuously monitor water quality parameters and fish behavior, while AI-based models optimize feeding, detect diseases, and support real-time decision-making. Automated imaging and surveillance systems further improve farm efficiency, reduce labor requirements, and enhance production performance.



Fig. 2. Integrated climate-smart technologies for resilient and sustainable aquaculture.

Ecosystem-Based Management

Ecosystem-based management promotes aquaculture development while maintaining ecological balance and conserving biodiversity. This approach emphasizes habitat protection, efficient resource utilization, pollution control, and the integration of aquaculture with surrounding ecosystems. By considering ecological, social, and economic factors, ecosystem-based management supports resilient and environmentally sustainable aquaculture production.

Adaptation and Mitigation Strategies

Climate-resilient adaptation and mitigation strategies are essential for ensuring the long-term sustainability of aquaculture under changing environmental conditions. Key approaches include:

- **Diversification of cultured species:** Farming climate-tolerant and multiple aquatic species reduces production risks, enhances resilience, and provides stable income under variable environmental conditions.
- **Climate-resilient infrastructure development:** Construction of improved ponds, reinforced cages, water storage facilities, and efficient drainage systems helps minimize damage caused by floods, cyclones, droughts, and other extreme weather events.
- **Early warning systems for extreme events:** Weather forecasting, satellite-based monitoring, and real-time environmental surveillance enable farmers to prepare for cyclones, heatwaves, floods, harmful algal blooms, and disease outbreaks, reducing economic losses.
- **Policy interventions and governance frameworks:** Effective government policies, financial support, insurance schemes, climate-smart management practices, and farmer capacity-building programs strengthen the adaptive capacity of the aquaculture sector.
- **Reduction of greenhouse gas emissions:** Improving feed efficiency, adopting renewable energy sources, optimizing water management, and promoting low-carbon aquaculture technologies help reduce greenhouse gas emissions and support environmentally sustainable production.

The implementation of these adaptation and mitigation strategies can enhance the resilience, productivity, and sustainability of aquaculture while safeguarding livelihoods and ensuring future food security.

Benefits of Climate-Smart Technologies in Aquaculture

Climate-smart technologies improve the sustainability, productivity, and resilience of aquaculture systems under changing climatic conditions. These technologies enhance water and feed use efficiency, reduce greenhouse gas emissions, strengthen disease management, and improve environmental monitoring. Advanced systems such as RAS, Biofloc, AI-based monitoring, and precision aquaculture optimize resource utilization while minimizing production risks. In addition, climate-smart approaches increase farm profitability, ensure stable fish production, and contribute to food and nutritional security.

Challenges and Limitations

Despite their advantages, the adoption of climate-smart technologies is constrained by several challenges. High initial investment costs, limited technical expertise, inadequate infrastructure, and restricted access to finance hinder widespread implementation, particularly among small-scale farmers. In addition, poor digital connectivity, insufficient training, and lack of policy support limit the effective use of advanced technologies. Addressing these barriers is essential for promoting inclusive and sustainable aquaculture development.

Future Perspectives

The future of climate-smart aquaculture lies in the integration of artificial intelligence, the Internet of Things (IoT), remote sensing, genomics, renewable energy, and precision farming technologies. Continued research and innovation will support the development of climate-resilient species, efficient production systems, and low-carbon aquaculture practices. Strengthening policy frameworks, technology transfer, farmer training, and public-private partnerships will accelerate the adoption of sustainable technologies and improve the resilience of the aquaculture sector to climate change.

Conclusion

Climate change poses significant challenges to aquaculture by affecting water quality, fish health, productivity, and the livelihoods of millions of people. The adoption of climate-smart technologies, including Recirculating Aquaculture Systems (RAS), Biofloc Technology, Integrated Multi-Trophic Aquaculture (IMTA), artificial intelligence, and digital monitoring, provides effective solutions for improving resource efficiency, reducing environmental impacts, and enhancing climate resilience. Continued investment in research, innovation, infrastructure, and supportive policies will be essential to ensure sustainable aquaculture development, strengthen global food security, and protect aquatic ecosystems in the face of future climate uncertainties.

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MODERN TECHNOLOGIES AND INNOVATIONS IN AQUACULTURE

Krishna Karshan Bhai Chopara*

M.F.Sc. Student, Department of Aquaculture, College of Fisheries Science,
Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Aquaculture is the fastest-growing food production sector globally and involves the farming of fish, crustaceans, molluscs, and aquatic plants under controlled or semi-controlled conditions. Global aquaculture production has increased significantly over the past few decades due to the rising demand for high-protein food and advances in farming technologies, reaching approximately 130.9 million tonnes, including 94.4 million tonnes of aquatic animals and 36.5 million tonnes of algae. Despite its important role in food security, nutrition, and livelihoods, the sector faces several sustainability challenges, including poor water quality, dependence on fishmeal and fish oil, disease outbreaks, biodiversity loss, habitat degradation, and nutrient pollution. To address these challenges, innovative approaches such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Aquaponics, and Integrated Multi-Trophic Aquaculture (IMTA) have been developed to improve water management and resource utilization. In addition, technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), automated systems, biotechnology, genetic improvement, and alternative feed ingredients are enhancing production efficiency and sustainability. These technological, ecological, and management innovations contribute to maintaining ecological balance, improving production efficiency, and supporting the long-term sustainability of aquaculture.

Recent Advances in Sustainable Aquaculture

Sustainability challenges in aquaculture have led to the development and adoption of advanced technologies that improve resource utilization, reduce environmental impacts, and enhance production efficiency. In recent years, several innovative techniques have been introduced worldwide to address these challenges and promote sustainable aquaculture practices.

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are among the most advanced and environmentally friendly technologies in modern aquaculture. These closed-loop systems reuse 90–95% of water, greatly reducing freshwater consumption, waste discharge, and environmental impacts while providing better control over culture conditions. RAS uses mechanical filters to remove suspended solids such as uneaten feed and feces, biological filters containing nitrifying microorganisms to convert toxic ammonia into less harmful nitrate, and UV irradiation for pathogen control. Additional components, including temperature regulation and oxygenation units, help maintain optimal condition. Recent advancements in RAS include the use of ozonation and UV disinfection to improve water quality by reducing organic matter and harmful microorganisms without leaving chemical residues. Furthermore, newly identified nitrifying microorganisms such as ammonia-oxidizing archaea (AOA) and comammox Nitrospira have enhanced biofiltration efficiency by improving ammonia removal under low-ammonia and low-oxygen conditions, making RAS more stable and efficient for intensive aquaculture.

Biofloc Technology (BFT)

Biofloc Technology (BFT) is an innovative and environmentally friendly aquaculture system that relies on beneficial microorganisms to recycle nutrients within the culture unit. The microbial community, consisting of bacteria, algae, protozoa, and organic matter, converts uneaten feed and fish waste into bioflocs, which serve as a natural protein-rich feed for cultured fish and shrimp. This process reduces water exchange, minimizes nutrient-rich waste discharge, improves feed utilization, and supports high-density aquaculture with better environmental control. A key management practice in BFT is maintaining an appropriate carbon-to-nitrogen (C:N) ratio by adding external carbon sources such as molasses, rice bran, wheat flour, tapioca flour, cassava powder, and jaggery. These low-cost agricultural by-products promote the growth of beneficial heterotrophic bacteria, improve water quality, and enhance nutrient recycling. However, poor C:N ratio management can cause oxygen depletion, accumulation of suspended solids, increased ammonia and nitrite levels, and disease outbreaks. Therefore, regular monitoring of carbon inputs and microbial balance is essential to ensure stable, efficient, and biosecure BFT operations.

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable farming system that combines fed species with extractive species, which utilize organic and inorganic wastes generated during aquaculture. Unlike traditional monoculture systems that often lead to nutrient accumulation and environmental pollution, IMTA promotes nutrient recycling by integrating organisms from different trophic levels. This approach reduces eutrophication, improves resource utilization, enhances environmental sustainability, and produces multiple marketable products, thereby increasing economic benefits and reducing production risks. IMTA differs from finfish polyculture because it integrates species with complementary ecological functions rather than species with similar biological requirements. In this system, seaweeds absorb dissolved inorganic nutrients, while other extractive organisms utilize organic wastes, creating a balanced ecosystem that improves farm management and supports environmentally responsible aquaculture practices.

Aquaponics

Aquaponics is an integrated farming system that combines aquaculture and hydroponics in a closed-loop cycle, where nutrient-rich water from fish tanks is used to grow plants, and the purified water is recirculated back to the fish tanks. The system achieves 95–99% water reuse, efficiently recycles nutrients, minimizes wastewater discharge, and reduces the need for external fertilizers and additional filtration systems. By simultaneously producing fish and plants, aquaponics improves resource utilization, sustainability, profitability, and contributes to food security. Recent advancements in aquaponics include improved system designs, algal co-cultivation, micro-nanobubble technology, advanced biofilter media, and automation using robotics, Artificial Intelligence (AI), and the Internet of Things (IoT). These innovations enable real-time monitoring of water quality, feeding, nutrient balance, and freshwater use, while modular, scalable, and vertical aquaponics systems have further enhanced space and resource efficiency, especially in urban farming.

Precision Aquaculture

Precision aquaculture is a technology-driven approach that improves aquaculture productivity through automation, real-time monitoring, and data-based management. It aims to replace traditional manual and experience-based farming with automated systems that provide better control over fish health and culture conditions. Advanced sensors continuously monitor important water quality parameters such as temperature, dissolved oxygen, nitrogen, salinity, pH, and turbidity, while camera- and computer vision-based systems enable non-invasive monitoring of

fish growth, behavior, and health. Recent developments include low-cost sensor networks, IoT-based monitoring, artificial intelligence (AI), machine learning, and deep learning models for water quality assessment, biomass estimation, disease detection, and feed management. Computer vision technologies have improved feeding precision and biomass estimation, while predictive models integrating GIS and machine learning support early disease forecasting. Although challenges such as high investment costs, sensor dependency, and data integration remain, precision aquaculture has significantly enhanced production efficiency, reduced feed costs, prevented disease outbreaks, and promoted environmental sustainability.

Genetic Improvement and Biotechnology

Genetic improvement and biotechnology are playing an important role in enhancing the sustainability, productivity, and resilience of aquaculture. Selective breeding has been widely used in species such as carp, tilapia, and salmon to improve growth performance, feed efficiency, and disease resistance. Advanced genomic tools, including marker-assisted selection and genomic selection, are further accelerating genetic improvement and addressing production challenges. In addition, health management strategies such as probiotics, immunostimulants, and oral vaccines help reduce antibiotic use and control bacterial diseases in cultured fish. Modern gene-editing technologies, particularly CRISPR-Cas9, have also emerged as promising tools for improving specific desirable traits. Together, these biotechnological advancements enhance production efficiency, improve fish health and product quality, and support sustainable aquaculture development.

Artificial Intelligence (AI), Internet of Things (IoT), and Automation

Artificial Intelligence (AI), the Internet of Things (IoT), and automation are revolutionizing modern aquaculture by enabling precision farming, real-time monitoring, and data-driven decision-making. IoT-based sensors continuously monitor critical water quality parameters, including temperature, dissolved oxygen, pH, salinity, and ammonia, transmitting real-time data to cloud-based platforms for analysis. AI algorithms process these datasets to optimize feeding schedules, predict growth performance, detect abnormal fish behavior, and provide early warnings of disease outbreaks, thereby reducing feed wastage and improving production efficiency. Automated feeding systems, robotic cleaners, and smart aeration devices further minimize labor requirements while enhancing operational accuracy and resource utilization. Collectively, these technologies improve productivity, reduce operational costs, strengthen biosecurity, and support sustainable aquaculture practices.

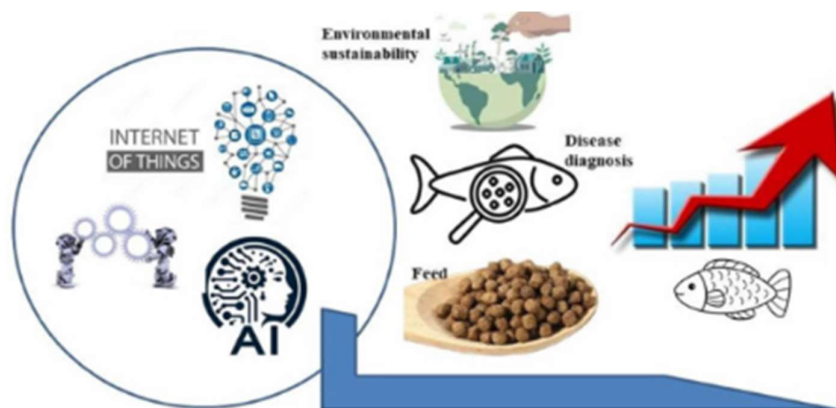


Fig. 1. Application of IoT, AI, and automation for precision aquaculture and sustainable farm management

Remote Sensing, GIS, and Drone Applications

Remote sensing, Geographic Information Systems (GIS), and unmanned aerial vehicles (drones) have become valuable tools for monitoring, planning, and managing aquaculture operations. Satellite imagery and GIS-based spatial analysis facilitate the identification of suitable aquaculture sites by evaluating environmental factors such as water quality, land use, topography, and climatic conditions. Drones provide high-resolution aerial imagery for pond inspection, infrastructure assessment, biomass estimation, and the detection of algal blooms, disease symptoms, or water quality anomalies. These technologies also support environmental monitoring, disaster assessment, and resource mapping, enabling farmers and policymakers to make informed management decisions. The integration of remote sensing, GIS, and drone technology enhances farm efficiency, minimizes environmental impacts, and promotes sustainable aquaculture development.

Alternative Sustainable Feeds

The development of alternative sustainable feeds is an important advancement in aquaculture, reducing dependence on fishmeal and fish oil while addressing environmental and economic concerns. Sustainable feed ingredients such as single-cell proteins, microalgae, yeast, insect, meal, and agricultural by-products are increasingly being used in aquafeeds. These alternatives help conserve marine resources, reduce pressure on wild fisheries, support biodiversity conservation, and promote a circular bioeconomy by utilizing agricultural and food waste. Several sustainable feed ingredients have already been adopted commercially. Black soldier fly larvae meal has been successfully used as a protein source in salmon and shrimp diets, while microalgae-derived oils rich in omega-3 fatty acids effectively replace fish oil without affecting fish growth or fillet quality. Single-cell proteins from bacteria and yeast also provide high-quality protein and beneficial bioactive compounds that improve gut health and immunity. These alternative feeds enhance resource efficiency, reduce environmental impacts, and support the long-term sustainability of aquaculture.

Table 1. Modern innovations and their sustainability benefits in aquaculture

Technology /Ingredient	Core function /key characteristics	Sustainability impact
Recirculating Aquaculture Systems (RAS)	Minimizes water exchange with optimizing water quality and efficiency; maintains high FCR; integrates solar energy to reduce costs and enable year-round production	Excellent water efficiency and sustainability is enhanced by renewable energy
Biofloc Technology (BFT)	Recycle nutrients via microbial flocs; high FCR; low production cost	Reducing waste, increasing feed efficiency, and recycling nutrients
Aquaponics (AP)	Combines fish and plant production; plants enhance water quality; water is efficiently reused	Co-production of crops and resource efficiency
Integrated Multi-Trophic Aquaculture	Production is increased by recycling waste through integration of different species	Reduces waste and increases the efficiency of the ecosystem

Technology /Ingredient	Core function /key characteristics	Sustainability impact
Artificial Intelligence (AI), Internet of Things (IoT) and Automation	Real-time monitoring of water quality, feeding, fish health, and farm operations using sensors, AI, and automated systems	Improves production efficiency, reduces feed costs and disease risks, and supports precision aquaculture

Limitations of Advanced Technologies

Although advanced technologies have improved the sustainability of aquaculture, they also have several limitations. Recirculating Aquaculture Systems (RAS) require high initial investment, skilled labor, and continuous energy for aeration and biofiltration. Biofloc Technology (BFT) depends on continuous aeration and careful maintenance of the carbon-to-nitrogen (C:N) ratio to prevent oxygen depletion, excess suspended solids, and disease outbreaks. The adoption of Integrated Multi-Trophic Aquaculture (IMTA) is limited by site suitability, species compatibility, system complexity, and regulatory constraints, while aquaponics faces challenges such as high setup costs, nutrient deficiencies, limited crop options, and the need to maintain a balance among fish, plants, and microorganisms. Similarly, precision aquaculture is constrained by the high cost of sensors, data reliability issues, limited interoperability, and dependence on stable electricity and internet connectivity, particularly in developing countries. Genetic improvement and gene-editing technologies face concerns related to high costs, ethical and biosecurity issues, off-target mutations, patent restrictions, and public acceptance. In addition, alternative sustainable feeds may have inconsistent nutrient composition, antinutritional factors, amino acid deficiencies, lower omega-3 content, palatability problems, and risks of contaminants such as mycotoxins, heavy metals, and pesticide residues. These limitations should be addressed to ensure the wider adoption and long-term success of sustainable aquaculture technologies.

Future Perspectives

The future of sustainable aquaculture will be driven by the integration of advanced technologies, biotechnology, and ecosystem-based farming practices. Emerging tools such as Artificial Intelligence (AI), Machine Learning, the Internet of Things (IoT), and robotics will enable real-time monitoring, precision management, improved decision-making, and reduced environmental impacts. In developing countries, these technologies can be introduced gradually through affordable digital tools, mobile-based monitoring systems, simple sensor networks, and cooperative farming models supported by public-private partnerships, farmer training, government subsidies, and microcredit programs. Future progress will also depend on genetic improvement, CRISPR-Cas9 gene editing, and sustainable alternative feeds, which can enhance disease resistance, growth performance, feed efficiency, and reduce dependence on antibiotics, fishmeal, and fish oil. Climate-smart technologies such as renewable energy-powered RAS, improved Biofloc Technology (BFT), Integrated Multi-Trophic Aquaculture (IMTA), and aquaponics are expected to improve resource efficiency, nutrient recycling, and reduce carbon emissions. In addition, greater emphasis on sustainability certification, big data-based disease surveillance, and collaboration among farmers, researchers, policymakers, and technology providers will support resilient, environmentally responsible, and economically viable aquaculture, particularly benefiting small-scale farmers in developing countries.

Conclusion

Modern innovations are transforming aquaculture into a more sustainable, efficient, and environmentally responsible food production system. Technologies such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Aquaponics, Integrated Multi-Trophic Aquaculture (IMTA), precision aquaculture, Artificial Intelligence (AI), the Internet of Things (IoT), biotechnology, and alternative sustainable feeds have significantly improved water and nutrient use efficiency, feed management, disease control, and overall productivity. In addition, remote sensing, GIS, and drone technologies have enhanced site selection, environmental monitoring, and farm management through data-driven decision-making. Although challenges such as high investment costs, technical complexity, and infrastructure requirements remain, continued research, supportive policies, capacity building, and wider adoption of these innovations will accelerate the transition toward climate-resilient and resource-efficient aquaculture. Overall, the integration of advanced technologies with sustainable farming practices will play a crucial role in ensuring long-term food security, environmental conservation, and the sustainable growth of the global aquaculture sector.

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GIS AND REMOTE SENSING IN MODERN FISHERIES MANAGEMENT

Kadam Bihari*

Ph.D. Scholar, Department of Fisheries Resource Management,
College of Fisheries Science, Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Fisheries and aquaculture play a vital role in global food security, nutrition, employment, and economic development. According to the Food and Agriculture Organization (FAO, 2024), fisheries provide an important source of animal protein and livelihoods for millions of people worldwide. Sustainable management of aquatic resources requires accurate and timely information on fish distribution, habitat conditions, and environmental changes. However, conventional fisheries monitoring methods rely heavily on field surveys, which are often time-consuming, labor-intensive, and limited in spatial and temporal coverage. In recent decades, Geographic Information Systems (GIS) and Remote Sensing (RS) have emerged as powerful geospatial technologies for supporting modern fisheries management. These technologies enable the collection, integration, analysis, and visualization of spatial data, providing valuable information for resource assessment, environmental monitoring, and ecosystem management. The integration of GIS and Remote Sensing has significantly improved fisheries research, planning, and conservation, making them indispensable tools for sustainable fisheries and aquaculture development.

Importance of GIS and Remote Sensing in Fisheries

GIS and Remote Sensing have become essential tools in modern fisheries by providing accurate, timely, and spatial information for monitoring aquatic resources. These technologies improve fisheries planning, support sustainable resource utilization, and enable evidence-based decision-making while reducing the cost and time required for field surveys.

- **Identification of Potential Fishing Zones (PFZs):** Helps locate productive fishing areas using satellite-derived oceanographic data.
- **Aquatic Habitat Mapping:** Assists in mapping coral reefs, mangroves, wetlands, estuaries, and spawning and nursery grounds.
- **Water Quality Monitoring:** Monitors environmental parameters such as sea surface temperature, chlorophyll-a, turbidity, salinity, and dissolved sediments.
- **Fish Stock Assessment and Resource Management:** Supports the estimation of fish distribution, abundance, and migration patterns for sustainable fisheries management.
- **Conservation and Climate Change Monitoring:** Facilitates ecosystem conservation, biodiversity assessment, pollution monitoring, and evaluation of climate change impacts on fisheries.

Principles of GIS and Remote Sensing

Geographic Information System (GIS)

A Geographic Information System (GIS) is a computer-based system used to collect, store, manage, analyze, and visualize geographically referenced data. In fisheries, GIS integrates information from satellite imagery, field surveys, GPS, and environmental databases to produce spatial maps that

support resource assessment and decision-making. It is widely used for mapping aquatic habitats, identifying Potential Fishing Zones (PFZs), monitoring fish distribution, assessing water quality, and planning conservation strategies. GIS enables fisheries managers to analyze spatial relationships, detect environmental changes, and develop sustainable management plans for aquatic ecosystems.

Remote Sensing (RS)

Remote Sensing (RS) is the science of acquiring information about the Earth's surface without direct physical contact by using sensors mounted on satellites, aircraft, or unmanned aerial vehicles (UAVs). In fisheries, remote sensing provides continuous and large-scale observations of environmental parameters such as sea surface temperature (SST), chlorophyll-a concentration, turbidity, salinity, ocean colour, and suspended sediments. These data are essential for identifying productive fishing grounds, monitoring habitat changes, assessing climate impacts, and supporting ecosystem-based fisheries management.

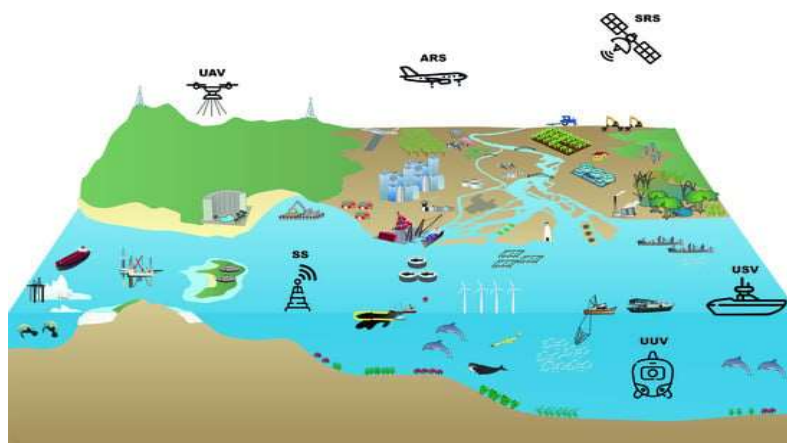


Fig. 1. Geospatial technologies for modern fisheries management.

Components of GIS

A GIS consists of five major components that work together to process and analyze spatial information:

- **Hardware:** Computers, GPS devices, servers, drones, and satellite receiving systems used for data processing and storage.
- **Software:** GIS software such as ArcGIS, QGIS, ERDAS Imagine, and Google Earth Engine used for mapping, spatial analysis, and visualization.
- **Data:** Spatial data (maps, satellite images, GPS coordinates) and attribute data (water quality, fish abundance, environmental variables).
- **People:** Scientists, fisheries managers, GIS analysts, policymakers, and other stakeholders who interpret and utilize geospatial information.
- **Methods:** Standardized procedures and analytical techniques used for data collection, processing, interpretation, and decision-making.

Types of Remote Sensing

Remote sensing systems are broadly classified into two categories:

Passive Remote Sensing: Passive sensors rely on natural energy, primarily sunlight reflected from the Earth's surface or emitted thermal radiation. Satellites such as Landsat, Sentinel-2, MODIS, and

VIIRS use passive sensors to monitor sea surface temperature, chlorophyll-a, ocean colour, vegetation, and water quality.

Active Remote Sensing: Active sensors emit their own electromagnetic energy and measure the reflected signal from the Earth's surface. Technologies such as Synthetic Aperture Radar (SAR) and LiDAR can acquire data during both day and night and under cloudy conditions. Active remote sensing is widely used for monitoring coastlines, detecting fishing vessels, mapping flood-affected areas, measuring water levels, and supporting maritime surveillance.

Applications of GIS and Remote Sensing in Modern Fisheries Management

Potential Fishing Zone (PFZ) Forecasting:

The integration of SST and chlorophyll-a data derived from MODIS, OCM-2, and VIIRS has enabled real-time identification of potential fishing zones. The Indian National Centre for Ocean Information Services (INCOIS) issues daily PFZ advisories via SMS and mobile apps, leading to 30–40 percent fuel savings and improved catch efficiency for small-scale fishermen. PFZ forecasts combine RS-derived parameters with GIS-based spatial modeling of bathymetry and ocean currents.

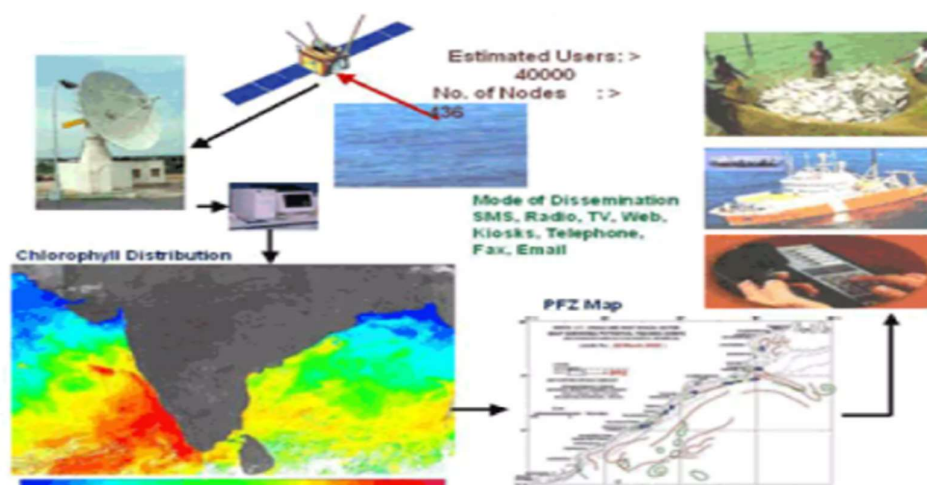


Fig. 2. Potential Fishing Zone (PFZ) forecasting using satellite remote sensing.

Marine Habitat Mapping:

High-resolution optical and radar data facilitate the delineation of coral reefs, seagrass beds, and mangroves-critical habitats for many fish species. GIS change-detection analyses between Landsat archives have revealed coral bleaching patterns and mangrove degradation in the Gulf of Mannar and Sundarbans.

Monitoring Illegal, Unreported, and Unregulated (IUU) Fishing:

Synthetic Aperture Radar (SAR) imagery combined with Automatic Identification System (AIS) vessel data enables detection of non-compliant fishing vessels even under cloudy or night conditions. GIS-based tracking of vessel trajectories supports enforcement and maritime security.

Oceanographic and Climate Monitoring:

Long-term RS datasets are crucial for assessing El Niño–Southern Oscillation impacts on SST anomalies and consequent shifts in fish stock distributions. GIS-enabled spatio-temporal analyses help anticipate changes in tuna and sardine fisheries linked to climatic oscillations.

Advanced Geospatial Technologies:**Unmanned Aerial Vehicles (UAVs):**

Drones provide centimeter-scale imagery, enabling fine-scale monitoring of pond dykes, feed distribution, and disease outbreaks. Thermal sensors on UAVs can detect localized temperature anomalies indicating potential stress zones.

Artificial Intelligence (AI) and Machine Learning (ML):

AI-driven classification improves detection accuracy of algal blooms and habitat types. Convolutional Neural Networks (CNNs) have been used to automate coral-reef health assessment and to predict fish-school distributions from RS imagery.

Internet of Things (IoT) and Real-Time Monitoring:

Smart sensors deployed in aquaculture ponds transmit real-time data on temperature, salinity, and dissolved oxygen. When linked to GIS dashboards, these networks allow proactive management—adjusting aeration or feed schedules to maintain optimal conditions.

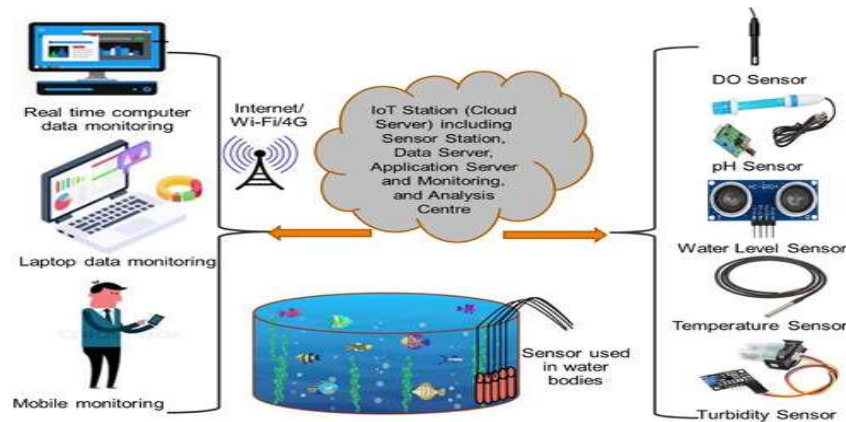


Fig. 3. Real-time IoT monitoring of aquatic environmental parameters.

Cloud-Based Geospatial Platforms:

Platforms such as Google Earth Engine (GEE), ArcGIS Online, and QGIS Cloud facilitate large-scale processing of time-series data and collaboration among researchers. These tools democratize access to computational power previously restricted to specialized institutions.

Benefits of GIS and Remote Sensing in Fisheries

Geographic Information Systems (GIS) and Remote Sensing (RS) offer numerous benefits for modern fisheries by improving the efficiency, accuracy, and sustainability of resource management. These technologies enable rapid assessment of fish habitats, water quality, and environmental conditions over large geographic areas, reducing the need for extensive field surveys and lowering operational costs. They support the identification of Potential Fishing Zones (PFZs), improve fish stock assessment, and facilitate habitat conservation and biodiversity monitoring. In addition, GIS and Remote Sensing provide real-time spatial information for disaster management, climate change assessment, and ecosystem-based fisheries management. Their ability to integrate and analyze geospatial data helps scientists, fisheries managers, and policymakers make informed decisions, ensuring the sustainable utilization and long-term conservation of aquatic resources.

Challenges and Limitations

Despite their significant advantages, the application of GIS and Remote Sensing in fisheries faces several challenges. The high cost of satellite data, specialized software, and technical infrastructure can limit their adoption, particularly in developing countries. Effective use of these technologies requires trained personnel and expertise in geospatial data analysis. In addition, cloud cover, limited spatial or temporal resolution, and the need for regular field validation may reduce the accuracy of remote sensing data. Limited access to real-time datasets, inadequate institutional support, and data-sharing constraints also hinder their effective implementation. Addressing these challenges through capacity building, affordable technologies, and improved data accessibility is essential for maximizing the benefits of GIS and Remote Sensing in fisheries management.

Future Scope of GIS and Remote Sensing in Fisheries and Aquaculture

The future of GIS and Remote Sensing in fisheries and aquaculture is highly promising due to rapid advancements in satellite technology, artificial intelligence (AI), unmanned aerial vehicles (UAVs), and cloud-based geospatial platforms. These technologies will enable real-time monitoring of fish stocks, water quality, disease outbreaks, and environmental changes with greater accuracy and efficiency. In aquaculture, GIS and Remote Sensing will support site selection, farm planning, precision aquaculture, and climate-resilient production systems. The integration of geospatial technologies with AI, Internet of Things (IoT), and big data analytics will further enhance decision-making, improve resource utilization, reduce production risks, and promote sustainable fisheries and aquaculture development. As these technologies become more affordable and accessible, their adoption is expected to increase worldwide, contributing significantly to food security, environmental conservation, and the blue economy.

Conclusion

GIS and Remote Sensing have become indispensable tools for modern fisheries and aquaculture by providing accurate, timely, and spatial information for resource assessment, environmental monitoring, and sustainable management. Their applications in habitat mapping, Potential Fishing Zone (PFZ) identification, water quality monitoring, and fish stock assessment have significantly improved the efficiency of fisheries management. Although challenges such as high costs, technical expertise, and data limitations remain, continuous technological advancements are expanding their accessibility and effectiveness. The integration of GIS and Remote Sensing with emerging technologies will play a crucial role in ensuring sustainable fisheries, enhancing aquaculture productivity, conserving aquatic ecosystems, and supporting global food security in the future.

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BLUE AQUACULTURE: DRIVING SUSTAINABLE FISHERIES GROWTH IN INDIA

Krishna Karshan Bhai Chopara*

M.F.Sc. Student, Department of Aquaculture, College of Fisheries Science,
Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Blue aquaculture has emerged as a key pillar of sustainable fisheries development and the blue economy, offering an environmentally responsible approach to increasing aquatic food production while conserving marine and coastal ecosystems. It encompasses the farming of marine and brackishwater organisms, including finfish, crustaceans, molluscs, and seaweeds, using sustainable production practices and advanced technologies. With global demand for seafood increasing and capture fisheries reaching their biological limits, blue aquaculture provides a viable solution for enhancing food security, improving nutrition, generating employment, and supporting economic growth without placing additional pressure on natural fish stocks. In recent years, innovations such as offshore cage culture, recirculating aquaculture systems (RAS), biofloc technology (BFT), integrated multi-trophic aquaculture (IMTA), precision aquaculture, and renewable energy-based farming have further strengthened the sustainability and productivity of the sector. As a major component of the Blue Economy, blue aquaculture promotes efficient resource utilization, biodiversity conservation, climate resilience, and responsible management of marine resources, making it an essential pathway for achieving sustainable fisheries development in India and worldwide.

Concept of Blue Aquaculture

Blue aquaculture is the sustainable farming of marine and brackishwater aquatic organisms, including finfish, crustaceans, molluscs, seaweeds, and other valuable aquatic resources, using environmentally responsible and economically viable production systems. It is a key component of the Blue Economy, which promotes the sustainable utilization of ocean and coastal resources to enhance food security, employment, livelihoods, and economic growth while conserving marine ecosystems. Unlike conventional aquaculture, blue aquaculture emphasizes ecosystem-based management, efficient resource utilization, biodiversity conservation, climate resilience, and the adoption of modern technologies to minimize environmental impacts. Advanced production systems such as marine cage culture, offshore aquaculture, Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Integrated Multi-Trophic Aquaculture (IMTA), aquaponics, and precision aquaculture improve water-use efficiency, nutrient recycling, disease management, and production performance. By integrating scientific innovation, sustainable farming practices, and responsible resource management, blue aquaculture supports long-term fisheries development, strengthens coastal economies, and contributes to the conservation of marine biodiversity while meeting the growing global demand for safe and nutritious aquatic food.

Status and Growth of Blue Aquaculture in India

India has emerged as one of the world's leading fisheries and aquaculture-producing countries, with blue aquaculture playing an increasingly important role in the growth of the fisheries sector.

The country possesses over 7,500 km of coastline, an Exclusive Economic Zone (EEZ) of about 2.02 million km², vast brackishwater areas, estuaries, lagoons, mangroves, and island ecosystems that provide immense opportunities for sustainable marine aquaculture. India's total fish production has increased from 95.79 lakh tonnes in 2013–14 to approximately 197.75 lakh tonnes in 2024–25, supported by rapid expansion of shrimp farming, marine cage culture, seaweed cultivation, shellfish farming, and mariculture. Government initiatives such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY), Blue Revolution, and PM-MKSSY, along with technological advancements and increasing private investment, have accelerated the development of blue aquaculture. With growing emphasis on sustainable production, export-oriented farming, climate-resilient technologies, and value addition, blue aquaculture is expected to become a major driver of India's fisheries growth, coastal livelihoods, food security, and the country's Blue Economy.

Major Components of Blue Aquaculture

Blue aquaculture comprises a diverse range of farming systems that utilize marine and brackishwater resources for the sustainable production of aquatic organisms. These components contribute significantly to food security, employment, export earnings, and the conservation of coastal ecosystems. With the adoption of modern technologies and improved management practices, each component plays a distinct role in strengthening India's blue economy and promoting sustainable fisheries development.

Marine Finfish Aquaculture

Marine finfish aquaculture involves the farming of commercially important marine fish species in coastal waters, sea cages, ponds, and recirculating aquaculture systems. Species such as Asian seabass (*Lates calcarifer*), cobia (*Rachycentron canadum*), silver pompano (*Trachinotus blochii*), and groupers (*Epinephelus* spp.) are widely cultured because of their rapid growth, high market value, and export potential. Advances in hatchery technology, formulated feeds, health management, and offshore cage farming have significantly improved production efficiency and sustainability. Marine finfish farming also reduces fishing pressure on wild stocks while creating new livelihood opportunities for coastal communities.

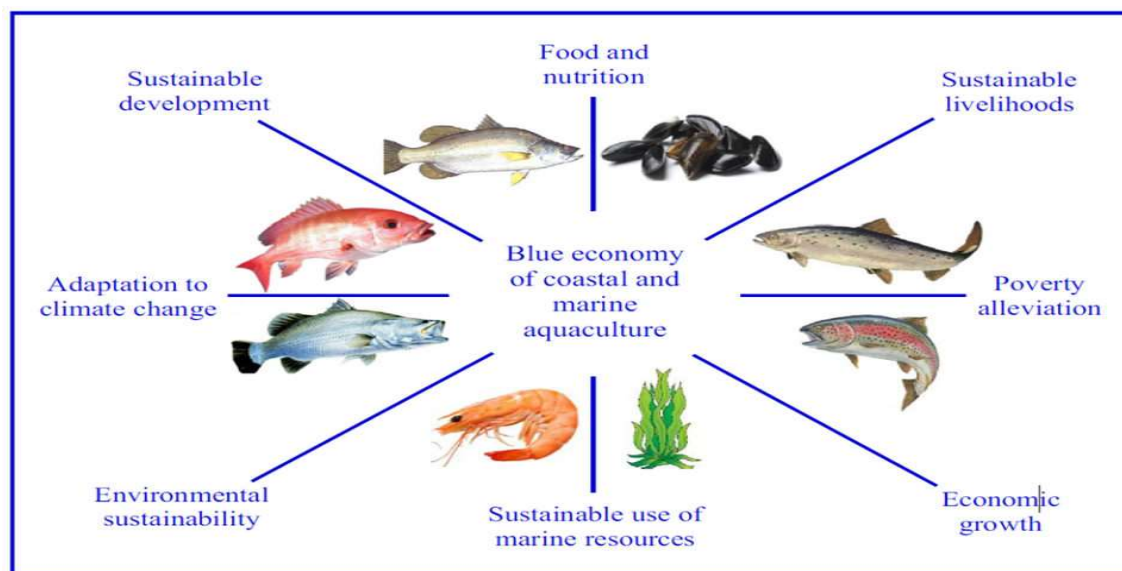


Figure 1. Major components of blue aquaculture supporting sustainable fisheries growth in India.

Brackishwater Shrimp Farming

Brackishwater shrimp farming is the largest and most economically important component of India's blue aquaculture sector. The culture of Pacific white shrimp (*Litopenaeus vannamei*) and black tiger shrimp (*Penaeus monodon*) has expanded rapidly due to high productivity, strong export demand, and improved farming technologies. The adoption of biosecure culture practices, high-quality seed, formulated feeds, aeration systems, and real-time water quality monitoring has enhanced production while reducing disease risks. Shrimp farming contributes substantially to foreign exchange earnings, employment generation, and the overall growth of India's seafood export industry.

Mariculture and Cage Culture

Mariculture refers to the farming of aquatic organisms in marine environments, whereas cage culture involves rearing fish in floating or submerged cages installed in coastal waters, reservoirs, estuaries, and sheltered bays. These farming systems efficiently utilize underexploited water resources without requiring large land areas. Cage culture is increasingly used for species such as seabass, cobia, pompano, and groupers because it allows better water exchange, high stocking densities, and faster growth. The integration of automated feeding systems, environmental monitoring, and improved cage designs has further enhanced productivity, making mariculture an important strategy for expanding sustainable fish production.

Seaweed and Shellfish Farming

Seaweed and shellfish farming are environmentally sustainable components of blue aquaculture that require minimal external inputs and provide significant ecological and economic benefits. Seaweeds such as *Kappaphycus*, *Gracilaria*, and *Ulva* are cultivated for food, pharmaceuticals, cosmetics, fertilizers, and biofuel production, while shellfish including oysters, mussels, clams, and pearl oysters are farmed for both domestic consumption and export markets. These organisms naturally absorb excess nutrients and improve water quality, helping to reduce eutrophication and enhance coastal ecosystem health. Their cultivation also supports carbon sequestration, biodiversity conservation, livelihood diversification, and climate-resilient aquaculture development.

Technological Innovations Supporting Blue Aquaculture

Technological innovations have become the driving force behind the sustainable growth of blue aquaculture by improving productivity, resource efficiency, and environmental performance. Advanced farming technologies such as offshore cage culture, Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Integrated Multi-Trophic Aquaculture (IMTA), aquaponics, and precision aquaculture have significantly enhanced water quality management, feed utilization, disease control, and production efficiency. In addition, digital tools including Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, Geographic Information Systems (GIS), drones, and automated feeding systems enable real-time monitoring of farm conditions, optimize resource use, and support informed decision-making. These innovations reduce production costs, minimize environmental impacts, and strengthen the resilience of blue aquaculture under changing climatic conditions.

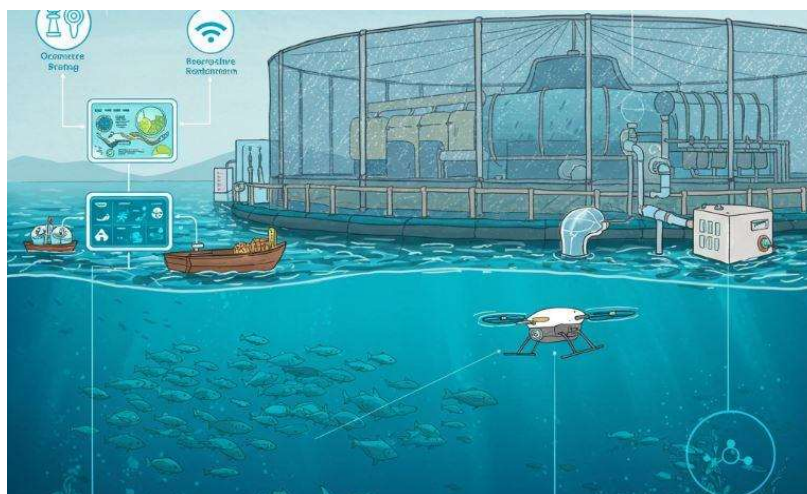


Figure 2. Modern technologies supporting sustainable blue Aquaculture

Government Initiatives and Policy Support

The Government of India has launched several initiatives to accelerate the development of blue aquaculture and promote sustainable fisheries growth. Flagship programmes such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY), Blue Revolution, Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY), and the Fisheries and Aquaculture Infrastructure Development Fund (FIDF) have strengthened infrastructure, hatchery development, quality seed production, cold-chain facilities, value addition, and market access. Research and extension support provided by ICAR, ICAR-CMFRI, and other fisheries institutions has facilitated the adoption of modern aquaculture technologies. These policy interventions have enhanced investment, improved coastal livelihoods, increased seafood exports, and contributed significantly to the growth of India's Blue Economy.

Economic and Environmental Benefits

Blue aquaculture offers substantial economic, social, and environmental benefits by increasing fish production while ensuring the sustainable use of marine and coastal resources. The sector generates employment opportunities, enhances farmers' income, supports export earnings, and strengthens national food and nutritional security. Environmentally, sustainable farming practices such as seaweed cultivation, shellfish farming, IMTA, and biofloc systems improve nutrient recycling, reduce pollution, conserve biodiversity, and enhance ecosystem resilience. The adoption of climate-smart technologies further improves water-use efficiency, lowers greenhouse gas emissions, and promotes responsible resource management, making blue aquaculture an essential component of sustainable coastal development.

Challenges and Opportunities

Despite its enormous potential, blue aquaculture faces several challenges, including high initial investment, disease outbreaks, limited availability of quality seed and feed, environmental degradation, climate change, regulatory constraints, and inadequate infrastructure in many coastal regions. Small-scale farmers often encounter financial, technical, and marketing limitations that restrict technology adoption. However, expanding domestic seafood demand, increasing export opportunities, technological advancements, private-sector investment, and improved government support present significant opportunities for future growth. The sustainable utilization of India's

vast marine resources can further strengthen fisheries production while ensuring environmental conservation and livelihood security.

Future Perspectives

The future of blue aquaculture in India will depend on the integration of advanced technologies, sustainable resource management, and supportive policy frameworks. Wider adoption of AI, IoT, automation, renewable energy, climate-resilient farming systems, selective breeding, and sustainable feed technologies is expected to improve productivity, reduce environmental impacts, and enhance resilience to climate change. Greater investment in research, digital infrastructure, capacity building, value-chain development, and public-private partnerships will accelerate the commercialization of innovative aquaculture technologies. With continued emphasis on ecosystem-based management, environmental sustainability, and responsible production practices, blue aquaculture is expected to play a central role in achieving food security, increasing seafood exports, generating coastal employment, and advancing India's vision of a sustainable Blue Economy.

Conclusion

Blue aquaculture has emerged as a sustainable and innovative approach for driving the growth of India's fisheries sector by integrating environmentally responsible farming practices with advanced technologies and effective resource management. The adoption of marine finfish culture, brackishwater shrimp farming, mariculture, seaweed and shellfish farming, along with modern technologies such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Artificial Intelligence (AI), the Internet of Things (IoT), and precision aquaculture, has significantly enhanced productivity, resource-use efficiency, and environmental sustainability. Supported by progressive government initiatives and increasing technological innovations, blue aquaculture has strengthened food and nutritional security, export earnings, employment generation, and coastal livelihoods while promoting the conservation of marine ecosystems. Although challenges such as climate change, disease outbreaks, and infrastructure constraints remain, continued investment in research, climate-smart technologies, policy support, and capacity building will accelerate the sustainable expansion of the sector. With its vast marine resources and growing technological capabilities, India is well positioned to harness the full potential of blue aquaculture, making it a key driver of sustainable fisheries development, economic growth, and the long-term success of the Blue Economy.

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RENEWABLE ENERGY SOLUTIONS FOR SUSTAINABLE FISH FARMING

Krishna Karshan Bhai Chopara*

M.F.Sc. Student, Department of Aquaculture, College of Fisheries Science,
Kamdhenu University, Veraval–362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Aquaculture has emerged as one of the most important sectors for ensuring global food security, improving nutrition, generating employment, and supporting sustainable economic development. However, the rapid expansion and intensification of fish farming have substantially increased energy requirements for essential operations such as water pumping, aeration, water circulation, temperature regulation, feeding systems, lighting, and post-harvest handling. Traditionally, these activities rely heavily on fossil fuel-based energy sources, which contribute to rising production costs, greenhouse gas emissions, and environmental degradation. As concerns over climate change, energy security, and environmental sustainability continue to grow, the adoption of renewable energy has become an essential component of modern aquaculture. Renewable energy technologies, including solar, wind, biogas, hydropower, and biomass, offer clean, reliable, and environmentally friendly alternatives that can reduce dependence on conventional fuels while improving energy efficiency and lowering operational costs. Furthermore, integrating renewable energy with advanced aquaculture technologies enhances resource utilization, minimizes environmental impacts, and supports climate-resilient fish production systems. Therefore, the transition towards renewable energy-based aquaculture is increasingly recognized as a key strategy for achieving sustainable fish farming, conserving natural resources, and ensuring the long-term productivity and resilience of aquatic food production systems.

Importance of Renewable Energy in Fish Farming

Renewable energy plays a crucial role in promoting sustainable and environmentally responsible fish farming by providing clean, reliable, and cost-effective alternatives to conventional fossil fuels. Modern aquaculture depends heavily on energy for water pumping, aeration, recirculating aquaculture systems (RAS), feeding, lighting, temperature control, and post-harvest operations.



Fig.1 Renewable Energy in Fish Farming

The use of renewable energy technologies such as solar, wind, biogas, hydropower, and biomass help reduce greenhouse gas emissions, lowers operational costs, improves energy security, and minimizes the environmental footprint of aquaculture. Furthermore, renewable energy enables fish farming in remote and off-grid areas where access to reliable electricity is limited, thereby enhancing productivity and supporting sustainable rural development.

Importance of Renewable Energy in Fish Farming

- **Reduces Production Costs:** Lowers long-term expenditure on electricity and fossil fuels, improving farm profitability.
- **Minimizes Environmental Pollution:** Reduces greenhouse gas emissions, carbon footprint, and dependence on non-renewable energy sources.
- **Enhances Energy Security:** Provides a reliable and continuous energy supply, particularly in remote and off-grid aquaculture farms.
- **Supports Sustainable Aquaculture:** Improves resource-use efficiency while promoting environmentally friendly fish production systems.
- **Improves Water Quality Management:** Ensures uninterrupted operation of aerators, pumps, and filtration systems, maintaining optimal water quality.
- **Strengthens Climate Resilience:** Reduces vulnerability to fuel price fluctuations and supports climate-smart aquaculture practices.
- **Promotes Rural Development:** Expands access to affordable energy, creating employment opportunities and improving livelihoods in rural communities.
- **Contributes to Sustainable Development Goals (SDGs):** Supports clean energy adoption, climate action, responsible production, and food security through sustainable aquaculture practices.

Major Renewable Energy Sources for Aquaculture

Renewable energy technologies provide clean, reliable, and sustainable alternatives to conventional energy sources in aquaculture. They help reduce operational costs, minimize greenhouse gas emissions, and improve the energy efficiency of fish farming systems. The major renewable energy sources used in aquaculture are described below.

Solar Energy

Solar energy is the most widely adopted renewable energy source in aquaculture due to its abundance, low operating cost, and ease of installation. Photovoltaic (PV) panels convert sunlight into electricity to power water pumps, aerators, recirculating aquaculture systems (RAS), feeders, lighting, and monitoring equipment. Solar-powered systems are particularly beneficial for remote and off-grid fish farms where access to grid electricity is limited.

Wind Energy

Wind energy utilizes wind turbines to generate electricity for aquaculture operations. It can be used to operate water pumps, aerators, and other electrical equipment, especially in coastal and open-land farming areas with consistent wind resources. Wind power reduces dependence on fossil fuels and can be combined with solar energy in hybrid systems to ensure a more stable and continuous power supply.

Biogas Energy

Biogas is produced through the anaerobic digestion of organic materials such as fish waste, animal manure, agricultural residues, and other biodegradable wastes. The generated biogas can be used

for electricity generation, heating, and water pumping in aquaculture farms. Besides producing renewable energy, biogas technology also helps manage organic waste, reduces environmental pollution, and generates nutrient-rich slurry that can be used as organic fertilizer.

Hydropower

Hydropower generates electricity by utilizing the kinetic energy of flowing or falling water. Small-scale hydropower systems are suitable for aquaculture farms located near rivers, streams, or irrigation canals. Hydropower provides a reliable and continuous source of clean electricity for pumps, aerators, hatcheries, and water circulation systems while producing minimal greenhouse gas emissions.

Biomass Energy

Biomass energy is produced by converting organic materials such as crop residues, forestry waste, fish-processing by-products, and other agricultural biomass into heat or electricity through combustion, gasification, or other conversion technologies. Biomass energy offers an environmentally friendly option for meeting the energy demands of aquaculture while promoting efficient utilization of agricultural and fishery wastes, reducing waste disposal problems, and supporting sustainable resource management.

Table 1. Major Renewable Energy Sources and Their Applications in Aquaculture

Renewable Energy Source	Major Applications in Fish Farming	Key Benefits
Solar Energy	Water pumping, aeration, lighting, RAS, automatic feeders	Low operating cost, clean energy, suitable for remote farms
Wind Energy	Water pumps, aerators, electricity generation	Reduces fossil fuel use, reliable in windy coastal areas
Biogas Energy	Electricity generation, heating, water pumping	Converts organic waste into energy, reduces waste disposal problems
Hydropower	Pumps, hatcheries, water circulation systems	Continuous and reliable power with low greenhouse gas emissions
Biomass Energy	Heat and electricity generation for aquaculture facilities	Utilizes agricultural and fishery wastes, supports sustainable resource management

Applications of Renewable Energy in Fish Farming

Renewable energy has become an integral component of modern aquaculture by providing reliable and environmentally sustainable power for various farm operations. The integration of renewable energy technologies improves production efficiency, reduces operational costs, minimizes greenhouse gas emissions, and enhances the sustainability of fish farming systems. Major applications include the following:

Water Pumping and Aeration

Renewable energy, particularly solar and wind power, is widely used to operate water pumps and aerators in fish ponds and tanks. Continuous pumping ensures an adequate water supply, while aeration maintains optimal dissolved oxygen levels, improves water quality, reduces fish stress, and enhances growth, survival, and overall productivity.

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) require a continuous supply of electricity to operate pumps, filtration units, aerators, ultraviolet (UV) sterilizers, oxygenation systems, and monitoring devices. Renewable energy sources such as solar photovoltaic systems and hybrid solar–wind systems provide reliable power, reducing energy costs and ensuring uninterrupted operation of intensive aquaculture systems.

Hatcheries and Nursery Units

Fish hatcheries and nursery facilities depend on a stable energy supply for water circulation, aeration, temperature regulation, incubation systems, lighting, and live-feed production. Renewable energy helps maintain optimum environmental conditions for egg incubation, larval rearing, and fingerling production, thereby improving seed quality, survival rates, and overall hatchery performance.

Cold Storage and Processing

Renewable energy is increasingly used to operate cold storage units, ice-making plants, refrigeration systems, and fish processing facilities. Solar-powered refrigeration and hybrid renewable energy systems help preserve fish quality, extend shelf life, reduce post-harvest losses, and improve the efficiency of fish handling, transportation, and marketing while lowering dependence on conventional electricity and fossil fuels.



Fig. 2. Solar-powered cold storage for fish processing.

Benefits of Renewable Energy in Sustainable Aquaculture

The adoption of renewable energy technologies has significantly improved the sustainability and efficiency of modern aquaculture. By replacing conventional fossil fuel-based energy sources with clean and renewable alternatives, fish farms can reduce operating costs, minimize environmental impacts, and ensure a reliable energy supply. Renewable energy also supports climate-resilient aquaculture by improving resource efficiency and promoting environmentally responsible production practices. The major benefits are outlined below.

- **Reduced Operational Costs:** Renewable energy decreases long-term expenditure on electricity and fossil fuels, improving the profitability and economic sustainability of fish farming.

- **Lower Greenhouse Gas Emissions:** The use of solar, wind, biogas, and other renewable energy sources reduces carbon emissions and minimizes the environmental footprint of aquaculture operations.
- **Improved Energy Security:** Renewable energy provides a stable and reliable power supply, particularly in remote and off-grid aquaculture farms where electricity availability is limited.
- **Enhanced Water Quality Management:** Continuous operation of pumps, aerators, filtration systems, and water circulation equipment helps maintain optimum water quality and improves fish health.
- **Higher Productivity and Farm Efficiency:** Reliable energy supports uninterrupted farm operations, leading to better growth performance, higher survival rates, and increased production efficiency.
- **Sustainable Waste Utilization:** Biogas and biomass technologies convert organic wastes into useful energy, reducing environmental pollution while improving resource utilization.
- **Climate Change Mitigation:** Renewable energy contributes to climate-smart aquaculture by reducing dependence on fossil fuels and increasing the resilience of fish farming systems to climate-related challenges.
- **Support for Sustainable Development:** The adoption of renewable energy promotes environmentally responsible aquaculture, conserves natural resources, creates rural employment opportunities, and contributes to long-term food security and sustainable economic development.

Challenges and Limitations

Despite its numerous environmental and economic benefits, the adoption of renewable energy in aquaculture faces several technical, financial, and operational challenges. High installation costs, limited technical expertise, and the intermittent nature of renewable energy sources often restrict their widespread implementation, particularly in small-scale fish farms. In addition, inadequate infrastructure, insufficient policy support, and maintenance requirements can affect the efficiency and long-term performance of renewable energy systems. Addressing these challenges through technological advancements, financial incentives, and capacity-building programs is essential for achieving sustainable and climate-resilient aquaculture.

- **High Initial Investment:** The installation of solar panels, wind turbines, biogas plants, and other renewable energy systems requires substantial capital investment.
- **Intermittent Energy Supply:** Solar and wind energy depend on weather conditions, leading to fluctuations in electricity generation and the need for energy storage or backup systems.
- **Limited Technical Expertise:** The operation, maintenance, and repair of renewable energy technologies require skilled personnel, which may not be readily available in many farming regions.
- **Infrastructure and Maintenance Constraints:** Inadequate infrastructure, limited access to spare parts, and regular maintenance requirements can reduce system efficiency and increase operational challenges.
- **Financial and Policy Barriers:** Limited access to credit, insufficient government incentives, and weak policy implementation may discourage farmers from adopting renewable energy technologies.

- **Site-Specific Limitations:** The effectiveness of renewable energy systems depends on local environmental conditions, such as solar radiation, wind availability, water resources, and biomass availability, which vary across locations.

Conclusion

Renewable energy has become a key driver of sustainable fish farming by providing clean, reliable, and environmentally friendly alternatives to conventional fossil fuel-based energy sources. The integration of solar, wind, biogas, hydropower, and biomass technologies into aquaculture operations improves energy efficiency, reduces production costs, lowers greenhouse gas emissions, and enhances the sustainability of fish farming systems. Although challenges such as high initial investment, technical limitations, and infrastructure constraints remain, continued technological advancements, supportive government policies, and increased awareness can accelerate the adoption of renewable energy in aquaculture. The widespread use of renewable energy will play a vital role in promoting climate-resilient aquaculture, conserving natural resources, ensuring long-term food security, and achieving sustainable fisheries and aquaculture development.

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CONSERVING ENDANGERED FRESHWATER FISH SPECIES IN INDIA

Kadam Bihari*

Ph.D. Scholar, Department of Fisheries Resource Management,
College of Fisheries Science, Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Freshwater ecosystems are among the most biologically diverse yet highly threatened ecosystems in the world, supporting a remarkable diversity of fish species that are essential for ecological balance, food security, and human livelihoods. However, rapid urbanization, river regulation through dams, excessive water abstraction, pollution, habitat fragmentation, overexploitation, invasive species, and climate change have caused severe degradation of freshwater habitats, resulting in a rapid decline in fish biodiversity. Freshwater fishes are now recognized as one of the most threatened groups of vertebrates, with extinction rates exceeding those of many terrestrial vertebrates. The loss of fish diversity not only threatens individual species but also disrupts ecosystem functioning, food webs, and fisheries productivity. These growing challenges highlight the urgent need for effective conservation strategies that integrate habitat protection, restoration, and sustainable management. Establishing Freshwater Aquatic Sanctuaries (FAS) within rivers, wetlands, lakes, and other protected freshwater ecosystems has emerged as a promising conservation approach, providing secure habitats for breeding, feeding, and migration while safeguarding endangered fish species and their genetic diversity for future generations.

Importance of Conservation of Endangered Freshwater Fish

The conservation of endangered freshwater fish is essential for maintaining aquatic biodiversity, ecological balance, and the sustainability of freshwater ecosystems. Freshwater fishes play important roles in nutrient cycling, food-web dynamics, and ecosystem functioning while supporting inland fisheries, food security, and the livelihoods of millions of people. Many endangered species also represent valuable genetic resources that are important for future aquaculture, fisheries improvement, and scientific research. Protecting these species helps preserve ecosystem resilience, prevents biodiversity loss, and ensures the sustainable utilization of freshwater resources for future generations.

Major Threats to Freshwater Fish Diversity

Freshwater fish diversity in India is declining rapidly due to increasing anthropogenic and environmental pressures. Habitat degradation caused by river regulation, dam construction, wetland destruction, and excessive water extraction has reduced suitable breeding and feeding habitats. Industrial effluents, agricultural runoff, sewage discharge, and plastic pollution have severely deteriorated water quality, affecting fish health and reproduction. Overfishing, destructive fishing practices, and the introduction of invasive alien species further threaten native fish populations by disrupting ecological balance and increasing competition for resources. In addition, climate change, including rising water temperatures, altered rainfall patterns, floods, and droughts, has modified river hydrology and habitat conditions, placing many freshwater fish species at greater risk of population decline and extinction.

Major Endangered Freshwater Fish Species in India

India possesses one of the richest freshwater fish diversities in the world, with more than 2,200 fish species, ranking among the global freshwater megadiversity countries. Its extensive network of rivers, streams, wetlands, reservoirs, lakes, estuaries, mangroves, ponds, and floodplain ecosystems supports a wide range of economically and ecologically important fish species, many of which contribute significantly to inland fisheries and rural livelihoods. However, increasing anthropogenic pressures, including habitat degradation, river regulation, pollution, overexploitation, and the introduction of exotic species, have resulted in a rapid decline in freshwater fish populations. Assessments conducted by the National Bureau of Fish Genetic Resources (NBFGR) and the Conservation Assessment and Management Plan (CAMP) have identified a large number of Indian freshwater fishes as threatened, including critically endangered and endangered species such as *Tor putitora*, *Tor tor*, *Pangasius pangasius*, *Ompok pabda*, *Chitala chitala*, and *Horabagrus brachysoma*. Despite their conservation significance, comprehensive information on species distribution, habitat requirements, and population status within protected freshwater ecosystems remains limited. Recent studies conducted in protected areas have highlighted the importance of freshwater habitats as refuges for threatened fish species and emphasized the need for scientifically managed Freshwater Aquatic Sanctuaries (FAS), supported by geospatial tools and long-term biodiversity monitoring, to ensure the conservation of India's valuable freshwater fish genetic resources.

Table 1. Major Endangered Freshwater Fish Species of India

S.No.	Common Name	Scientific Name	IUCN Status	Major Distribution in India
1	Golden Mahseer	<i>Tor putitora</i>	Endangered (EN)	Himalayan rivers (Ganga, Yamuna, Beas)
2	Deccan Mahseer	<i>Tor khudree</i>	Endangered (EN)	Krishna, Godavari and Cauvery Rivers
3	Giant Devil Catfish	<i>Bagarius yarrelli</i>	Near Threatened (NT)	Ganga, Brahmaputra and Himalayan rivers
4	Butter Catfish	<i>Ompok bimaculatus</i>	Near Threatened (NT)	Ganga, Brahmaputra and Northeast India
5	Freshwater Shark	<i>Wallago attu</i>	Vulnerable (VU)	Major rivers throughout India
6	Indian Trout	<i>Barilius barna</i>	Vulnerable (VU)	Himalayan foothill streams
7	Pabda Catfish	<i>Ompok pabda</i>	Endangered (EN)	Ganga–Brahmaputra Basin
8	Malabar Mahseer	<i>Tor malabaricus</i>	Endangered (EN)	Western Ghats
9	Denison Barb	<i>Sahyadria denisonii</i>	Endangered (EN)	Western Ghats (Kerala)
10	Redline Torpedo Barb	<i>Sahyadria chalakkudiensis</i>	Endangered (EN)	Chalakkudy River, Kerala

Species Diversity and Assessment in Protected Areas

Studies conducted in protected freshwater ecosystems of India have demonstrated that these areas play a vital role in conserving fish biodiversity and safeguarding threatened species. For example, the Gerua River within the Katarniaghat Wildlife Sanctuary (KWS) supports a rich assemblage of 87 fish species belonging to 22 families and 52 genera, with the family Cyprinidae

being the most dominant. The sanctuary provides suitable habitats for several economically and ecologically important species, including *Tor putitora*, *Tor tor*, *Pangasius pangasius*, *Chitala chitala*, *Catla catla*, *Clupisoma garua*, and *Ompok bimaculatus*. Comparative assessments revealed significantly higher fish diversity, abundance, and larger size classes within the protected area than in adjacent unprotected river stretches. Notably, nearly one-third of the threatened freshwater fish species recorded by NBFGR were found to maintain stable populations within the sanctuary, highlighting the importance of protected freshwater habitats in conserving endangered fish germplasm. Furthermore, the application of GIS-based habitat mapping and species distribution analysis has improved the identification of critical habitats and different life stages of fishes, providing valuable scientific information for habitat management and long-term freshwater biodiversity conservation.



Fig. 1. Major Endangered Freshwater Fish Species of India

Conservation Strategies for Endangered Freshwater Fish

The conservation of endangered freshwater fish requires an integrated approach that combines habitat protection, scientific management, captive propagation, policy support, and community participation. Effective conservation strategies should focus on maintaining healthy aquatic ecosystems, restoring degraded habitats, reducing anthropogenic pressures, and ensuring the sustainable utilization of fish resources. The major conservation approaches are discussed below.

In-situ Conservation

In-situ conservation involves protecting fish species within their natural habitats by conserving rivers, lakes, wetlands, and associated ecosystems. This approach includes the establishment of protected areas, fish sanctuaries, environmental flow management, pollution control, and regulation of destructive fishing practices. Conserving natural habitats helps maintain ecological processes, genetic diversity, and sustainable fish populations.

Ex-situ Conservation

Ex-situ conservation refers to the protection and maintenance of endangered fish species outside their natural habitats in facilities such as hatcheries, aquaria, research institutions, and gene

banks. This strategy is particularly important for critically endangered species with declining wild populations and provides a safeguard against extinction while supporting future restoration programmes.

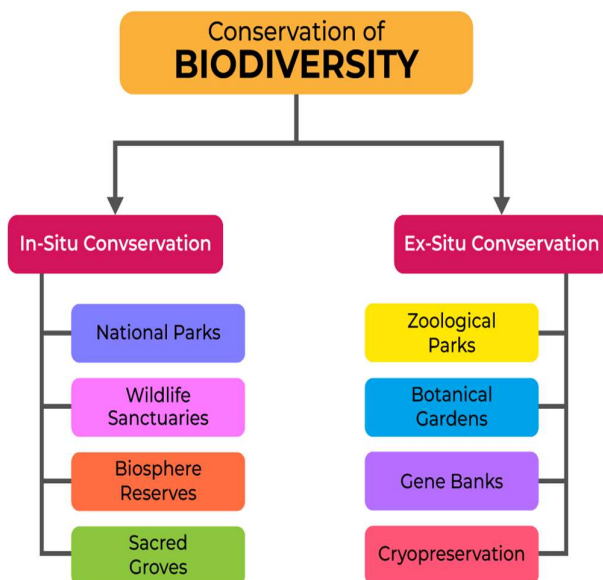


Fig. 2. Types and methods of biodiversity conservation

Captive Breeding and Stock Enhancement

Captive breeding programmes are designed to propagate endangered fish species under controlled conditions and produce healthy juveniles for reintroduction into natural water bodies. Stock enhancement through scientifically planned restocking helps restore depleted populations, improve genetic diversity, and strengthen inland fisheries when combined with habitat conservation.

Habitat Restoration

Habitat restoration aims to recover degraded freshwater ecosystems by improving water quality, restoring river connectivity, protecting wetlands, removing barriers to fish migration, controlling invasive species, and conserving riparian vegetation. Healthy habitats provide suitable conditions for feeding, breeding, migration, and long-term survival of native fish species.

Policy and Community Participation

Effective conservation depends on strong environmental policies, enforcement of fisheries regulations, scientific monitoring, and active participation of local communities. Public awareness, stakeholder involvement, sustainable fishing practices, and collaboration among government agencies, research institutions, and non-governmental organizations are essential for ensuring the long-term conservation of endangered freshwater fish species in India.

Role of Government and Conservation Organizations

The conservation of endangered freshwater fish species requires coordinated efforts from government agencies, research institutions, and conservation organizations. In India, organizations such as the Ministry of Environment, Forest and Climate Change (MoEFCC), the Department of Fisheries, the National Biodiversity Authority (NBA), the Central Inland Fisheries Research Institute

(ICAR–CIFRI), and various State Fisheries Departments play a vital role in protecting freshwater biodiversity through policy formulation, habitat restoration, scientific research, captive breeding programmes, and sustainable fisheries management. Conservation organizations, including the International Union for Conservation of Nature (IUCN), the WorldWide Fund for Nature (WWF), and national non-governmental organizations (NGOs), support biodiversity assessments, species recovery programmes, awareness campaigns, and community-based conservation initiatives. The combined efforts of these institutions strengthen the conservation of endangered freshwater fish species by promoting scientific management, legal protection, habitat conservation, and public participation.

Challenges and Limitations

The conservation of endangered freshwater fish species faces several ecological, technical, and socio-economic challenges. One of the major difficulties is identifying priority habitats and fish species that require immediate protection, as conservation needs vary across different river basins and freshwater ecosystems. Habitat degradation, pollution, river regulation, overfishing, invasive aquatic weeds, and illegal fishing continue to threaten native fish populations and reduce the effectiveness of conservation programmes. In many regions, water releases for irrigation are not synchronized with the breeding and migration requirements of fish, leading to habitat loss and increased vulnerability to poaching. Additional challenges include weak enforcement of environmental laws, limited financial and technical resources, fragmented management among different government agencies, and conflicts between fisheries conservation and local livelihood needs. Effective conservation therefore requires stronger institutional coordination, scientific monitoring, active participation of local communities, and integrated policies that balance biodiversity conservation with sustainable resource use.

Future Perspectives

The future of endangered freshwater fish conservation in India lies in the integration of advanced technologies, ecosystem-based management, and community participation. Emerging tools such as environmental DNA (eDNA), Geographic Information Systems (GIS), Remote Sensing, Artificial Intelligence (AI), and drone-based monitoring will enable accurate assessment of fish diversity, habitat quality, and population trends. Strengthening freshwater protected areas, restoring river connectivity, implementing climate-resilient conservation strategies, and expanding captive breeding and stock enhancement programmes will further enhance species recovery. In addition, improved policy implementation, long-term biodiversity monitoring, public awareness, and collaboration among government agencies, research institutions, and local communities will be essential to ensure the sustainable conservation of India's endangered freshwater fish species and their habitats.

Conclusion

The conservation of endangered freshwater fish species is essential for maintaining aquatic biodiversity, ecological balance, and sustainable fisheries. Increasing pressures from habitat degradation, pollution, overexploitation, invasive species, and climate change have placed many native fish species at risk of extinction, highlighting the need for immediate conservation action. An integrated approach combining in-situ and ex-situ conservation, habitat restoration, captive breeding, scientific research, supportive policies, and community participation is crucial for ensuring the long-term survival of these species. Strengthening collaboration among government agencies, research institutions, conservation organizations, and local communities will enhance

the effectiveness of conservation programmes and contribute to the sustainable management of India's valuable freshwater fish resources.

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PLASTIC POLLUTION AND ITS THREATS TO AQUACULTURE BIODIVERSITY

Kadam Bihari*

Ph.D. Scholar, Department of Fisheries Resource Management,
College of Fisheries Science, Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

Plastic pollution has become one of the most serious environmental challenges affecting freshwater and marine ecosystems worldwide. The extensive use of plastic materials in packaging, agriculture, fisheries, aquaculture, and other human activities, combined with poor waste management practices, has resulted in the continuous accumulation of plastic debris in rivers, lakes, wetlands, estuaries, and oceans. Due to their non-biodegradable nature, plastics persist in the environment for long periods and gradually break down into microplastics and nanoplastics, which are easily ingested by aquatic organisms. Plastic pollution threatens aquatic biodiversity through ingestion, entanglement, habitat degradation, and the transfer of toxic chemicals across aquatic food webs. Fish, crustaceans, mollusks, plankton, aquatic birds, turtles, and marine mammals are particularly vulnerable to its adverse effects, leading to reduced growth, impaired reproduction, physiological stress, and increased mortality. In aquaculture systems, plastic wastes such as fishing nets, ropes, feed bags, pond liners, and other equipment further contribute to environmental contamination and may affect cultured species, water quality, and seafood safety. Therefore, understanding the sources, distribution, ecological impacts, and management of plastic pollution is essential for protecting aquatic biodiversity, ensuring sustainable fisheries and aquaculture production, and safeguarding ecosystem and human health.

Sources and Types of Plastic Pollution

Plastic pollution in aquatic ecosystems originates from a wide range of land-based and water-based sources. Improper disposal of plastic waste, rapid urbanization, industrialization, and the extensive use of plastic products have resulted in the continuous accumulation of plastic debris in rivers, lakes, wetlands, estuaries, and oceans. These plastic materials persist for long periods and gradually fragment into smaller particles, posing serious threats to aquatic biodiversity and ecosystem health.

Land-Based Sources

Land-based activities contribute the majority of plastic pollution entering aquatic environments. Major sources include improperly managed municipal solid waste, single-use plastic products, industrial discharges, agricultural plastics, urban runoff, untreated sewage, and littering. During rainfall and flooding, these plastic materials are transported through drainage systems and rivers into freshwater and marine ecosystems, where they accumulate in water bodies and sediments.

Water-Based Sources

Water-based sources include abandoned, lost, or discarded fishing gear (ghost nets), aquaculture equipment, shipping and boating activities, offshore industries, and tourism-related waste. Plastics released directly into aquatic environments can entangle aquatic organisms, damage habitats, and gradually degrade into smaller particles that remain in the ecosystem for many years.

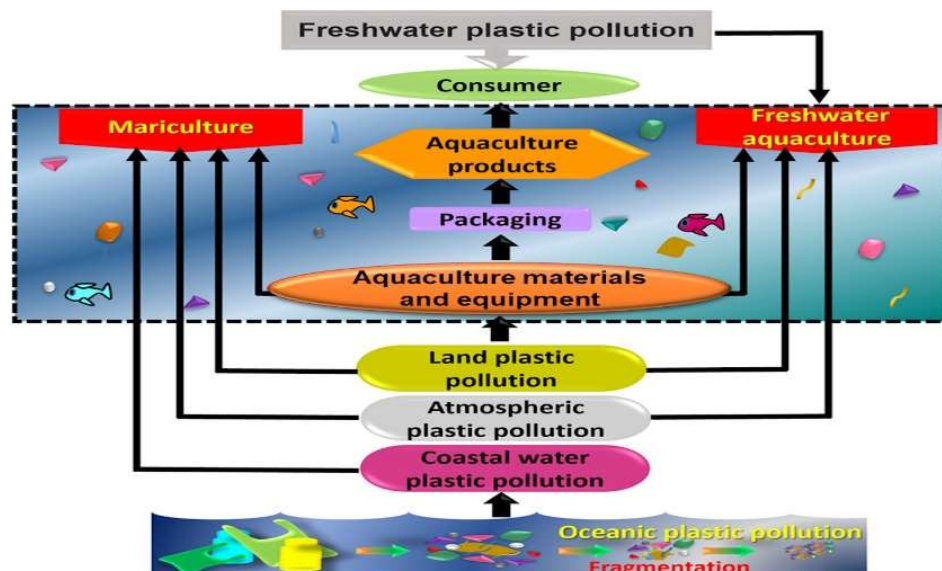


Figure 1. Plastic pollution pathways and their impacts on aquaculture systems.

Classification of Plastics

Based on their size, plastics are classified into four major categories. Macroplastics (>25 mm) include plastic bags, bottles, fishing nets, ropes, and other large debris that can cause entanglement and habitat degradation. Mesoplastics (5–25 mm) consist of fragmented plastic pieces that result from the breakdown of larger items. Microplastics (<5 mm) originate either as manufactured particles (primary microplastics) or from the fragmentation of larger plastics (secondary microplastics). They are readily ingested by fish, shellfish, plankton, and other aquatic organisms, allowing them to enter aquatic food webs. Nanoplastics (<1 μm) are extremely small particles capable of crossing biological membranes and accumulating within tissues and cells, raising growing concerns regarding aquatic organism health and food safety.

Table:1. Classification of Plastics and Their Ecological Impacts

Plastic Type	Size	Common Sources	Major Impacts on Aquatic Biodiversity
Macroplastics	>25 mm	Plastic bags, bottles, fishing nets, ropes, packaging materials	Entanglement of fish, turtles, birds, and marine mammals; habitat degradation
Mesoplastics	5–25 mm	Fragmented plastic containers, bottle caps, plastic pellets	Ingestion by fish and invertebrates; physical injury and reduced feeding efficiency
Microplastics	<5 mm	Cosmetic microbeads, synthetic fibers, degraded plastic debris	Bioaccumulation in fish, shellfish, and plankton; transfer of toxic chemicals through the food web
Nanoplastics	<1 μm	Further degradation of microplastics	Penetration into cells and tissues, oxidative stress, physiological disorders, and potential human health risks

Occurrence and Distribution of Plastics in Aquatic Environments

Plastic pollution is widely distributed throughout freshwater and marine ecosystems, including rivers, lakes, reservoirs, wetlands, estuaries, coastal waters, and the open ocean. Rivers serve as

major transport pathways, carrying plastic waste from urban, industrial, and agricultural areas to the sea, where it accumulates in surface waters, sediments, beaches, mangroves, coral reefs, and deep-sea environments. Large plastic debris gradually fragments into microplastics and nanoplastics through sunlight, wave action, and physical weathering, allowing these particles to spread throughout the aquatic environment. Microplastics have been detected in water, sediments, plankton, aquatic plants, fish, shellfish, crustaceans, and other aquatic organisms, demonstrating their widespread occurrence across different trophic levels. Ocean currents, tides, wind, and seasonal flooding further facilitate the movement and redistribution of plastics over long distances. Their persistence and continuous accumulation threaten aquatic biodiversity, ecosystem functioning, fisheries, and aquaculture, making plastic pollution a global environmental concern.

Impacts of Plastic Pollution on Aquatic Biodiversity

Plastic pollution poses a significant threat to aquatic biodiversity by affecting the survival, growth, reproduction, behavior, and overall health of aquatic organisms. Large plastic debris causes physical injuries, habitat degradation, and entanglement, while microplastics and nanoplastics are readily ingested by a wide range of aquatic species. In addition to causing internal damage, plastics can adsorb toxic chemicals, heavy metals, and pathogenic microorganisms, increasing their harmful effects on aquatic ecosystems. These impacts reduce biodiversity, disrupt ecological balance, and threaten the sustainability of fisheries and aquaculture.

Effects on Fish

Fish frequently mistake plastic particles for food and ingest them either directly from the water or indirectly through contaminated prey. Plastic ingestion can cause digestive blockages, reduced feeding efficiency, tissue damage, oxidative stress, impaired growth, reproductive disorders, behavioral changes, and increased mortality. Microplastics may also accumulate in fish tissues, affecting their physiological functions and reducing their commercial value.

Effects on Invertebrates

Aquatic invertebrates, including zooplankton, mollusks, crustaceans, worms, and benthic organisms, readily ingest microplastics because of their small size. Plastic ingestion reduces feeding efficiency, nutrient absorption, growth, survival, and reproductive success. The accumulation of plastics in these organisms can also alter community structure and negatively affect ecosystem productivity.

Effects on Aquatic Birds, Turtles, and Marine Mammals

Aquatic birds, sea turtles, dolphins, seals, whales, and other marine mammals are highly vulnerable to plastic pollution. They often ingest floating plastic debris or become entangled in discarded fishing nets, ropes, and other plastic materials. These interactions can lead to internal injuries, starvation, suffocation, restricted movement, reduced reproductive performance, and death. Habitat degradation caused by plastic waste further threatens the survival of these species.

Microplastics and Food Web Contamination

Microplastics enter the aquatic food web through plankton and other small organisms and are progressively transferred to fish, shellfish, marine mammals, and higher predators. During this process, plastics accumulate toxic contaminants such as heavy metals and persistent organic pollutants, increasing the risk of bioaccumulation and biomagnification. Ultimately, these

contaminants can reach humans through the consumption of contaminated seafood, posing potential risks to food safety, public health, and the long-term sustainability of aquatic ecosystems.

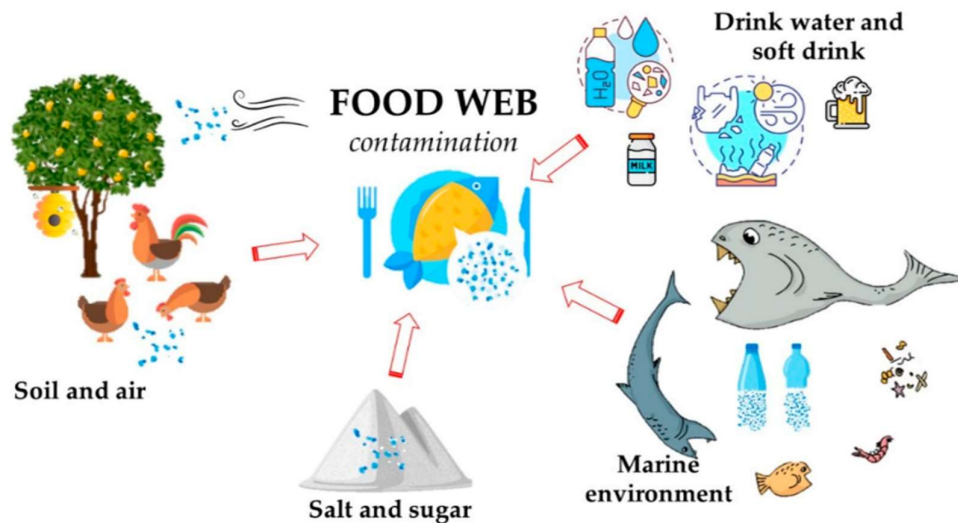


Figure 2. Schematic representation of microplastic transfer through the aquatic food web.

Plastic Pollution in Aquaculture Systems

Plastic pollution has become an emerging concern in aquaculture systems because plastic materials are widely used in fish and shrimp farming for nets, cages, ropes, feed bags, pond liners, floats, pipes, water storage tanks, and other farming equipment. Over time, these materials undergo weathering due to sunlight, temperature fluctuations, and mechanical abrasion, leading to the formation of microplastics and nanoplastics that contaminate culture water and sediments. Cultured fish, shrimp, mollusks, and other aquatic organisms may ingest these plastic particles, resulting in reduced feed intake, impaired growth, physiological stress, weakened immune responses, reproductive disorders, and increased susceptibility to diseases. Plastic waste can also deteriorate water quality, damage aquaculture infrastructure, and increase production costs through reduced productivity and equipment replacement. Therefore, adopting environmentally friendly farming practices, proper disposal and recycling of plastic materials, regular maintenance of aquaculture equipment, and the use of biodegradable alternatives are essential for minimizing plastic pollution and ensuring the sustainable development of aquaculture.

Ecological and Human Health Implications

Plastic pollution has far-reaching ecological and human health consequences by disrupting aquatic ecosystems and contaminating the food chain. The accumulation of plastic debris degrades aquatic habitats, reduces biodiversity, and alters ecological processes such as nutrient cycling and energy transfer. Microplastics are readily ingested by plankton, fish, shellfish, crustaceans, and other aquatic organisms, where they can accumulate toxic chemicals, heavy metals, and pathogenic microorganisms. These contaminants may be transferred through the food web and eventually reach humans through the consumption of contaminated seafood. Continuous exposure to microplastics and associated pollutants has raised concerns regarding food safety, human health, and ecosystem resilience. Therefore, reducing plastic pollution is essential to protect aquatic biodiversity, maintain ecosystem functioning, ensure sustainable fisheries and aquaculture production, and safeguard public health.

Monitoring and Management Strategies

Effective monitoring and management strategies are essential to reduce plastic pollution and protect aquatic biodiversity. Regular monitoring through field surveys, water and sediment quality assessments, microplastic analysis, and remote sensing helps identify pollution hotspots and evaluate the extent of contamination in aquatic ecosystems. Management measures should focus on reducing the use of single-use plastics, improving waste collection, segregation, recycling, and wastewater treatment, and promoting environmentally friendly and biodegradable alternatives. Strict enforcement of environmental regulations, extended producer responsibility, and sustainable fisheries and aquaculture practices can further minimize plastic inputs into water bodies. In addition, public awareness campaigns, community participation, educational programs, and international collaboration are crucial for preventing plastic pollution and ensuring the long-term conservation and sustainable management of freshwater and marine ecosystems.

Future Perspectives

The growing threat of plastic pollution highlights the need for innovative technologies, effective environmental policies, and sustainable resource management to protect aquatic ecosystems. Future strategies should focus on preventing plastic waste at its source, improving monitoring systems, and encouraging the adoption of environmentally friendly alternatives. Strengthening research, public awareness, and international cooperation will play a vital role in minimizing plastic pollution and conserving aquatic biodiversity for future generations.

- **Development of Biodegradable Alternatives:** Promote the use of biodegradable and eco-friendly materials to reduce dependence on conventional plastics in fisheries and aquaculture.
- **Advanced Monitoring Technologies:** Utilize remote sensing, environmental DNA (eDNA), artificial intelligence (AI), and IoT-based monitoring systems to detect and assess plastic pollution more efficiently.
- **Strengthening Policies and Waste Management:** Implement stricter environmental regulations, improve waste collection and recycling infrastructure, and encourage circular economy practices to minimize plastic leakage into aquatic environments.
- **Research, Education, and Public Awareness:** Enhance scientific research on the long-term impacts of microplastics while promoting environmental education and community participation to support sustainable plastic management.

Conclusion

Plastic pollution has emerged as one of the most serious environmental threats to freshwater and marine ecosystems, with far-reaching consequences for aquatic biodiversity, fisheries, and aquaculture. The widespread accumulation of macroplastics, microplastics, and nanoplastics in aquatic environments adversely affects fish, invertebrates, aquatic birds, turtles, marine mammals, and other organisms through ingestion, entanglement, habitat degradation, and the transfer of toxic contaminants. In aquaculture systems, plastic pollution compromises water quality, cultured species health, and overall production sustainability. Addressing this growing challenge requires an integrated approach involving effective waste management, reduced use of single-use plastics, adoption of biodegradable alternatives, regular monitoring, strict environmental regulations, and increased public awareness. Continued research, technological innovations, and international cooperation will be essential for minimizing plastic pollution, protecting aquatic biodiversity, and ensuring the long-term sustainability of fisheries, aquaculture, and aquatic ecosystems.

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RESTORING RIVER ECOSYSTEMS FOR HEALTHY FISH POPULATIONS

Kadam Bihari*

Ph.D. Scholar, Department of Fisheries Resource Management,
College of Fisheries Science, Kamdhenu University, Veraval-362265, Gujarat, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Introduction

River ecosystems are among the most dynamic and biologically diverse ecosystems on Earth. They provide habitat for numerous fish species, support livelihoods, supply drinking water, facilitate agriculture, and maintain ecological balance. However, over the past century, anthropogenic activities have significantly altered river systems, resulting in habitat degradation and declining fish populations. Fish habitat restoration has emerged as an important environmental management strategy for repairing degraded river ecosystems. It focuses on restoring the physical, chemical, and biological conditions required for the survival, reproduction, and growth of fish populations. By improving habitat complexity, water quality, and river connectivity, restoration initiatives not only enhance fish populations but also improve overall ecosystem functions and services. This chapter examines the principles, restoration methods, benefits, and challenges of fish habitat restoration in river ecosystems, highlighting its importance for sustainable aquatic ecosystem management.

Major Threats to River Ecosystems

Fish habitats in rivers are shaped by natural processes such as flow variation, sediment transport, vegetation growth and seasonal flooding. When these processes are disrupted, habitats deteriorate.

Pollution

River pollution from untreated sewage, industrial effluents, agricultural runoff, plastic waste, and toxic chemicals severely degrades water quality. These pollutants reduce dissolved oxygen, promote eutrophication, contaminate sediments, and threaten aquatic biodiversity. Long-term pollution also affects fish reproduction, disrupts food webs, and poses serious health risks to both wildlife and human populations.

Dam Construction and River Fragmentation:

Dams alter the natural flow of rivers, block fish migration routes, and disrupt sediment transport. Many migratory fish are unable to reach their upstream spawning grounds, reducing breeding success. River fragmentation isolates fish populations, limits gene flow, and decreases genetic diversity, ultimately threatening the health and sustainability of river ecosystems.



Fig. 1. Dam construction causing river fragmentation.

Sand Mining

Excessive sand mining alters river channels, destroys spawning and breeding habitats, increases bank erosion, and disturbs aquatic biodiversity. It also reduces habitat quality for fish and other aquatic organisms.



Fig. 2. Rock weirs for river habitat restoration.

Climate Change

Rising temperatures, altered rainfall patterns, floods, and droughts affect river flow, water quality, and aquatic habitats. These changes influence fish distribution, breeding, and overall ecosystem stability.

Invasive Species

Non-native species compete with native fish for food and habitat, prey on indigenous species, and spread diseases. This disrupts ecological balance and contributes to the decline of native biodiversity.

Impacts of River Degradation on Fish Diversity and Fisheries

River degradation has severe consequences for fish diversity and fisheries by reducing habitat quality, disrupting breeding and migration, and altering food availability. Pollution, dam construction, excessive sand mining, water extraction, and climate change contribute to the decline of native fish populations and the loss of sensitive species. Habitat fragmentation restricts gene flow and reduces reproductive success, while poor water quality increases disease outbreaks and fish mortality. These changes ultimately decrease fish production, threaten the livelihoods of fishing communities, and weaken the ecological integrity and long-term sustainability of river ecosystems.



Fig. 3. Impacts of river degradation on fish diversity and freshwater ecosystems

Principles of River Ecosystem Restoration

River ecosystem restoration aims to recover the natural structure, functions, and biodiversity of degraded rivers. It focuses on restoring natural flow regimes, improving water quality, reconnecting fragmented habitats, conserving native species, and enhancing ecological resilience. Effective restoration also involves sustainable watershed management, pollution control, community participation, and long-term monitoring to ensure the health and sustainability of river ecosystems.

Habitat Restoration Techniques**Dam Removal and Fish Passage Installation:**

Removing obsolete dams restores natural river flow, reconnects fragmented habitats, and improves sediment transport. Where dam removal is not feasible, fish ladders and bypass channels allow migratory fish to reach their spawning grounds. These measures enhance fish migration, improve breeding success, and help maintain healthy fish populations and genetic diversity.

In-Stream Habitat Enhancement:

Adding large woody debris, boulders, and engineered log jams enhances habitat complexity within rivers. These structures create pools, riffles, and shelter areas that provide feeding, breeding, and refuge habitats for fish. As a result, they improve fish survival, biodiversity, and the overall ecological health of river ecosystems.

Riparian Restoration:

Replanting native vegetation along riverbanks stabilizes soil, reduces erosion, filters pollutants, and helps regulate water temperature. Healthy riparian zones also provide food and shelter for aquatic organisms, support aquatic food webs, and improve the overall health of river ecosystems.

Spawning and Nursery Habitat Restoration:

Restoring spawning grounds and nursery habitats is essential for improving fish reproduction and juvenile survival. Rehabilitation of gravel beds, wetlands, floodplains and vegetated shallow areas provides suitable sites for egg laying and larval development. Reconnecting rivers with floodplains and maintaining environmental flows enhances natural spawning and recruitment. These restoration measures strengthen fish populations, increase biodiversity and support sustainable freshwater fisheries.

Biodiversity Conservation and Native Fish Species Recovery: Conserving biodiversity and restoring native fish species are essential for maintaining healthy freshwater ecosystems. Measures such as protecting critical habitats, controlling invasive species, improving water quality and implementing restocking programmes help recover declining native fish populations. These actions enhance ecosystem stability, preserve genetic diversity and strengthen the long-term sustainability of freshwater fisheries.

Protection of Critical Habitats: Conserve spawning grounds, nursery areas and migration routes to support the complete life cycle of native fish species.

Control of Invasive Species: Prevent the introduction and spread of non-native species that compete with or prey on indigenous fish populations.

Habitat Restoration and Water Quality Improvement: Restore degraded rivers and wetlands, reduce pollution and maintain environmental flows to create suitable conditions for native fish.

Restocking and Species Recovery Programmes: Release hatchery-bred native fish produced from genetically diverse broodstock and regularly monitor populations to enhance recovery success.

Community Participation and Integrated River Basin Management

Community participation and integrated river basin management are essential for the sustainable conservation and restoration of river ecosystems. The active involvement of local communities, fishers, farmers, government agencies and other stakeholders improves the planning and implementation of conservation measures. An integrated river basin approach considers the entire watershed, balancing ecological, social and economic needs while promoting the sustainable use of water resources. These strategies enhance ecosystem resilience, improve water quality and support long-term fisheries productivity and biodiversity conservation.

Modern Technologies in River Restoration

The application of modern technologies has significantly improved the planning, monitoring and evaluation of river restoration programmes. Advanced tools enable scientists and resource managers to assess river health, identify degraded habitats, monitor biodiversity and detect environmental changes with greater accuracy and efficiency. Technologies such as Geographic Information Systems (GIS), Remote Sensing, Environmental DNA (eDNA), Artificial Intelligence (AI) and Internet of Things (IoT)-based monitoring provide real-time data that support evidence-based decision-making, enhance conservation outcomes and promote sustainable river basin management.

Geographic Information System (GIS) and Remote Sensing

GIS and Remote Sensing are powerful spatial technologies used to map river networks, monitor land-use changes, assess water quality and identify degraded habitats. Satellite imagery and drone-based surveys provide continuous information on river morphology, vegetation cover, sediment transport, flood-prone areas and pollution hotspots. These tools help prioritize restoration sites, monitor habitat recovery and support watershed-scale planning and management.

Environmental DNA (eDNA)

Environmental DNA (eDNA) is an innovative molecular technique that detects genetic material released by aquatic organisms into water through skin cells, mucus, scales, faeces and reproductive products. It enables rapid, non-invasive and highly sensitive monitoring of fish diversity, endangered species and invasive organisms without the need for physical capture. eDNA has become an important tool for biodiversity assessment, early detection of invasive species and evaluating the effectiveness of river restoration programmes.

Artificial Intelligence (AI) and IoT-Based Monitoring

Artificial Intelligence (AI) integrated with Internet of Things (IoT)-based sensor networks enables continuous and real-time monitoring of river ecosystems. Smart sensors measure key environmental parameters such as water temperature, pH, dissolved oxygen, turbidity, conductivity and nutrient concentrations, while AI algorithms analyse large datasets to detect pollution events, predict ecological changes and support early warning systems. These technologies improve river management, enhance restoration efficiency and facilitate data-driven decision-making for sustainable freshwater ecosystem conservation.

Challenges and Future Perspectives

Despite significant advances in river restoration, several ecological, technical and socio-economic challenges continue to limit its long-term success. Habitat fragmentation caused by dams and other barriers, increasing pollution, climate change, overexploitation of water resources and the spread of invasive species remain major threats to freshwater ecosystems. Inadequate funding, weak policy implementation, limited long-term monitoring and poor coordination among stakeholders further reduce the effectiveness of restoration programmes. Addressing these challenges requires an integrated approach that combines scientific research, technological innovation, effective governance and active community participation.

Major Challenges

- Habitat fragmentation and altered river flow due to dams, channelization and water diversion.
- Pollution and climate change, leading to declining water quality, altered hydrological regimes and loss of aquatic biodiversity.
- Invasive species and overexploitation, which threaten native fish populations and disrupt ecosystem balance.
- Limited funding, monitoring and stakeholder coordination, resulting in poor implementation and evaluation of restoration projects.

Future Perspectives

- Adoption of advanced technologies such as GIS, Remote Sensing, Environmental DNA (eDNA), Artificial Intelligence (AI) and IoT for real-time monitoring and adaptive river management.
- Ecosystem-based river restoration, focusing on restoring natural river processes, ecological connectivity and environmental flows.
- Strengthening policy frameworks and community participation through integrated river basin management, public awareness and stakeholder collaboration.
- Long-term biodiversity conservation and climate resilience by protecting critical habitats, conserving native fish species and implementing continuous ecological monitoring to ensure sustainable freshwater ecosystems.

Conclusion

River ecosystem restoration is essential for conserving freshwater biodiversity and sustaining healthy fish populations. Restoring natural habitats, improving water quality, maintaining environmental flows and protecting native fish species enhance ecosystem resilience and fisheries productivity. The adoption of modern technologies such as GIS, Remote Sensing, eDNA, AI and IoT has significantly improved restoration planning and monitoring. However, challenges including pollution, habitat fragmentation, climate change and invasive species require continuous attention. Therefore, integrated river basin management, scientific research, strong policy support and active community participation are essential to ensure the long-term sustainability of river ecosystems and freshwater fisheries.

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AROMA MISSION: TRANSFORMING INDIAN AGRICULTURE THROUGH MEDICINAL AND AROMATIC CROPS

Ganga M¹, Sangamesh² and Yashaswini M. P³

¹Ph.D. Scholar, Department of Plantation, Spice, Medicinal and Aromatic Crops, University of Horticultural Sciences, Bagalkot 587104, Karnataka, India.

²Ph.D. Scholar, Department of Post Harvest Management (Center of Excellence), Navsari Agricultural University, Gujarat 396 450, India.

³Ph.D. Scholar, Department of Floriculture and Landscape Architecture, University of Horticultural Sciences Bagalkot 587104, Karnataka, India.

*Corresponding Email: gangamurthy2230@gmail.com

Abstract

The CSIR Aroma Mission is a flagship initiative launched by the Council of Scientific and Industrial Research (CSIR) to promote the cultivation, processing, value addition and commercialization of medicinal and aromatic crops across India. The mission aims to enhance farmers' income by introducing high-value aromatic crops such as menthol mint, lemongrass, citronella, palmarosa, basil, lavender, vetiver and patchouli in suitable agro-climatic regions. Through the development of improved varieties, advanced cultivation technologies, quality planting materials and efficient distillation techniques, the mission has significantly strengthened the aromatic crop sector. Besides generating employment and supporting rural entrepreneurship, it contributes to sustainable agriculture and reduces India's dependence on imported essential oils. This article highlights the objectives, achievements, major technologies and future prospects of the CSIR Aroma Mission in transforming Indian agriculture.

Keywords: CSIR Aroma Mission, Aromatic crops, Essential oils, Farmer income, Sustainable agriculture

Introduction

India is one of the world's richest countries in terms of medicinal and aromatic plant diversity. These crops are valued for their essential oils and bioactive compounds, which are widely used in the pharmaceutical, perfumery, cosmetics, food, personal care and aromatherapy industries. Compared with many conventional field crops, aromatic crops require relatively less land, offer higher economic returns, and provide excellent opportunities for value addition, making them attractive options for crop diversification and rural entrepreneurship. Recognizing this potential, the Council of Scientific and Industrial Research (CSIR) launched the Aroma Mission in 2016 under the Ministry of Science and Technology, Government of India. The mission aims to strengthen the entire value chain of aromatic crops by promoting improved varieties, scientific cultivation practices, quality planting material, efficient distillation technologies, value addition and market linkages. The initiative is coordinated by CSIR-Central Institute of Medicinal and Aromatic Plants (CSIR-CIMAP), Lucknow, with the support of several other CSIR laboratories across the country. The mission covers commercially important aromatic crops such as lemongrass, menthol mint, citronella, palmarosa, vetiver, patchouli, basil, lavender, damask rose and rosemary. These crops are being promoted in diverse agro-climatic regions, including drought-prone and marginal lands, providing farmers with profitable alternatives to traditional cropping systems. In addition to crop

production, the mission emphasizes entrepreneurship development through training programmes, establishment of distillation units, and promotion of value-added products derived from essential oils. The first two phases of the CSIR Aroma Mission successfully demonstrated the benefits of scientific interventions in aromatic crop cultivation, processing and product development. Building on these achievements, Phase III focuses on expanding cultivation, encouraging value addition and creating sustainable livelihood opportunities. By early 2025, approximately 43,000 hectares had been brought under Aroma Mission-supported cultivation against a target of 50,000 hectares, reflecting substantial progress in expanding the aromatic crop sector.

Objectives of the CSIR Aroma Mission

The **CSIR Aroma Mission** was launched with the vision of transforming India's medicinal and aromatic plant sector by integrating scientific research with commercial cultivation and market development. The mission focuses on improving farmers livelihoods while promoting sustainable agriculture through the cultivation of high-value aromatic crops.



Fig. 1. Major Objectives of the CSIR Aroma Mission

The mission adopts a "lab-to-land" approach by transferring technologies developed by **CSIR-CIMAP** and other CSIR laboratories directly to farmers through demonstrations, capacity-building programmes and technical support. This integrated strategy has helped establish aromatic crops as profitable alternatives for sustainable agricultural development and rural entrepreneurship.

Major Achievements of the CSIR Aroma Mission

Since its launch in 2016, the CSIR Aroma Mission has made remarkable progress in promoting the cultivation, processing and commercialization of medicinal and aromatic crops across India. The mission has successfully connected scientific innovations with farmers, entrepreneurs and industries thereby strengthening the aromatic crop sector and generating sustainable livelihood opportunities.

Expansion of Aromatic Crop Cultivation

One of the major achievements of the mission has been the significant expansion of the area under aromatic crop cultivation. Through continuous technical guidance and quality planting materials supplied by CSIR-Central Institute of Medicinal and Aromatic Plants (CSIR-CIMAP) and its collaborating institutes, thousands of farmers have adopted aromatic crops as profitable alternatives to conventional agriculture. The mission has expanded cultivation to diverse agro-climatic regions, including rainfed, wastelands and marginal lands, thereby utilizing underexploited agricultural resources effectively (Fig. 2).

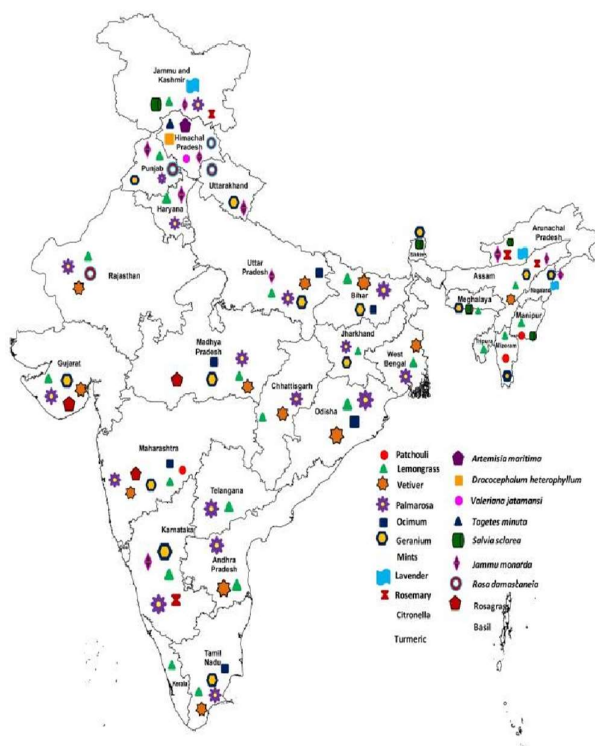


Fig. 2. Major States Covered under the CSIR Aroma Mission for the Promotion of Medicinal and Aromatic Crops

Development and Distribution of Improved Planting Materials

The mission has facilitated the large-scale production and distribution of superior quality planting materials of economically important aromatic crops such as lemongrass, menthol mint, citronella, palmarosa, vetiver, patchouli, basil, lavender and rosemary. Improved varieties with higher essential oil content, better adaptability and increased productivity have contributed significantly to improving farmers' income.

Technology Transfer and Capacity Building

A key strength of the Aroma Mission is its effective transfer of technologies from research laboratories to farmers' fields. Thousands of farmers, extension personnel, rural youth and entrepreneurs have received training on scientific cultivation practices, nursery management, harvesting techniques, essential oil extraction, quality improvement and post-harvest management. These programmes have enhanced technical knowledge and encouraged the adoption of modern production technologies.

Promotion of Distillation and Value Addition

The mission has promoted the installation of modern distillation units and processing facilities for efficient extraction of essential oils. Improved distillation technologies have enhanced oil recovery, maintained product quality and reduced processing losses. The mission also encourages value addition through the production of perfumes, cosmetics, herbal products, pharmaceuticals and other essential oil-based products, thereby creating additional employment and business opportunities.

Employment Generation and Rural Entrepreneurship

The cultivation and processing of aromatic crops have created numerous livelihood opportunities for farmers, women self-help groups, rural youth and small entrepreneurs. By promoting farmer-producer organizations, start-ups and micro-enterprises, the mission has strengthened rural entrepreneurship and improved income generation across several states.

Strengthening India's Essential Oil Industry

The Aroma Mission has contributed significantly to increasing domestic production of essential oils, thereby reducing dependence on imports and improving the availability of quality raw materials for industries. The initiative has also enhanced India's competitiveness in the global essential oil market through improved quality standards and scientific production technologies (Fig. 3.).

Overall, the CSIR Aroma Mission has demonstrated that aromatic crops can serve as profitable, climate-resilient and sustainable alternatives for agricultural diversification, while simultaneously supporting industrial growth and rural economic development.



Fig. 3. Major aromatic crops promoted under the CSIR Aroma Mission for essential oil production and value addition

Improved Varieties and Technologies Developed under the CSIR Aroma Mission

The CSIR Aroma Mission, led by CSIR-CIMAP, has strengthened India's aromatic crop sector through improved varieties, quality planting materials and advanced cultivation and processing technologies. These innovations have enhanced essential oil yield, oil quality and farmer's income. The mission has also promoted scientific crop management, modern distillation techniques, and sustainable production practices. Several high-yielding aromatic crop varieties with superior oil

quality and better adaptability have been introduced across different agro-climatic regions of the country.

Table 1. Major aromatic crop varieties promoted under the CSIR Aroma Mission

Crop	Improved variety	Important characteristics
Menthol mint (<i>Mentha arvensis</i>)	Kosi, Kushal, Himalaya	High herbage yield, high menthol content, suitable for commercial cultivation
Lemongrass (<i>Cymbopogon flexuosus</i>)	Krishna, Cauvery, Pragati	High citral content, excellent oil recovery, drought tolerant
Citronella (<i>Cymbopogon winterianus</i>)	Bio-13, Manjusha	High citronellal content, vigorous growth, superior oil quality
Palmarosa (<i>Cymbopogon martinii</i>)	Trishna	High geraniol content, good biomass production, quality essential oil
Vetiver (<i>Chrysopogon zizanioides</i>)	Gulabi, KS-1	High root yield, excellent vetiver oil quality, suitable for erosion control
Patchouli (<i>Pogostemon cablin</i>)	Johore, CIM-Samarth	High patchouli alcohol content, better biomass production
Basil (<i>Ocimum basilicum</i>)	CIM-Saumya, CIM-Snigdha	Rich in linalool, suitable for pharmaceutical and perfume industries
Lavender (<i>Lavandula angustifolia</i>)	Him Surabhi	Adapted to Himalayan regions, premium-quality essential oil
Rosemary (<i>Rosmarinus officinalis</i>)	CIM-Hariyali	High-quality aromatic oil, suitable for temperate regions

Note: The varieties listed are among those promoted and utilized through CSIR-CIMAP programmes under the Aroma Mission and related aromatic crop improvement initiatives.

Technologies Promoted under the Aroma Mission

Besides improved varieties, the mission has promoted several farmer-friendly technologies that enhance productivity and quality:

- Production and distribution of quality planting materials through certified nurseries.
- Scientific cultivation practices tailored to different agro-climatic regions.
- Drip irrigation and integrated nutrient management for efficient resource use.
- Improved harvesting methods to maximize essential oil recovery.
- Installation of modern steam distillation units for efficient extraction of essential oils.
- Post-harvest handling and quality assurance practices to maintain international standards.
- Capacity-building programmes, demonstrations, and entrepreneurship training for farmers and rural youth.

The adoption of these improved varieties and production technologies has significantly enhanced essential oil yield, product quality, and farmers' income while strengthening India's position in the global aromatic plant sector.

Success Stories and Impact of the CSIR Aroma Mission

The CSIR Aroma Mission has significantly transformed India's medicinal and aromatic crop sector by promoting scientific cultivation, improved planting materials, and modern distillation technologies. The mission has expanded aromatic crop cultivation across several states, enabling farmers to diversify into high-value crops and increase their income. A notable success is the promotion of lavender cultivation in Jammu & Kashmir, which has created new livelihood opportunities. By supporting essential oil extraction units, Farmer Producer Organizations (FPOs), and value-added enterprises, the mission has strengthened rural entrepreneurship and contributed to sustainable agricultural and economic development.

Future Prospects

The future of the CSIR Aroma Mission is highly promising due to the increasing global demand for natural essential oils, herbal products, cosmetics, pharmaceuticals, nutraceuticals, and aromatherapy products. As consumer preference shifts towards natural and plant-based products, medicinal and aromatic crops are expected to play an increasingly important role in India's agricultural economy.

Future efforts should focus on:

- Development of high-yielding and climate-resilient aromatic crop varieties.
- Expansion of aromatic crop cultivation in rainfed, marginal and degraded lands.
- Strengthening quality planting material production and certified nurseries.
- Establishment of additional modern distillation and processing units at the village level.
- Promotion of value addition, branding and export-oriented production.
- Greater adoption of precision farming, digital advisory services and climate-smart technologies.
- Capacity building of farmers, rural youth, women entrepreneurs and Farmer Producer Organizations (FPOs).
- Strengthening collaborations among research institutions, industries, government agencies, and private stakeholders to enhance innovation and market access.

With continued research, technological advancements, and effective policy support, the Aroma Mission has the potential to position India as a global leader in the production and export of high-quality essential oils and aromatic plant products.

Conclusion

The CSIR Aroma Mission has successfully demonstrated how scientific research, technology dissemination, and effective farmer participation can transform the cultivation of medicinal and aromatic crops into a sustainable and profitable agricultural enterprise. By promoting improved varieties, quality planting materials, scientific cultivation practices, modern distillation technologies, and value addition, the mission has significantly enhanced farmers' income, generated rural employment and strengthened India's essential oil industry.

Beyond its economic benefits, the mission contributes to sustainable agriculture, crop diversification, resource conservation, and rural entrepreneurship, thereby supporting the vision of Atmanirbhar Bharat and enhancing the livelihood security of farming communities. Continued investment in research, innovation, extension services and market development will further strengthen the aromatic crop sector and ensure long-term growth. The CSIR Aroma Mission stands as an excellent example of how science and agriculture can work together to create a prosperous, resilient and sustainable future for Indian farmers.

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RICE FORTIFICATION: A STRATEGY TO COMBAT MICRONUTRIENT DEFICIENCY

Sardar N. R*, Yoganandi Y. C, Srivastava S and Seth N

College of Agricultural Engineering & Technology Godhra,
Anand Agricultural University. Gujarat

*Corresponding Email: nileshrsardar@aau.in

Abstract

Rice is one of the most widely consumed staple foods globally, especially in Asian countries, where it serves as a major source of daily energy. However, polished rice contains limited amounts of essential micronutrients due to the removal of nutrient-rich bran and germ layers during milling. Rice fortification is an effective food-based approach to enhance the nutritional quality of rice by adding essential vitamins and minerals. This strategy helps address micronutrient deficiencies, particularly deficiencies of iron, zinc, folic acid, and vitamin A, among vulnerable populations. The present article discusses the concept, methods, benefits, challenges, and future prospects of rice fortification.

Keywords: Rice fortification, micronutrients, iron deficiency, vitamin enrichment, fortified rice kernels

Introduction

Micronutrient deficiencies, also known as hidden hunger, affect millions of people worldwide and are associated with poor health, reduced productivity, impaired cognitive development, and increased disease susceptibility. Rice is a primary staple food for more than half of the global population; however, conventional white rice provides mainly carbohydrates with low levels of essential micronutrients. During rice milling, the outer layers containing minerals, vitamins, and bioactive compounds are removed to improve appearance and shelf stability. As a result, nutrients such as iron, zinc, vitamin B-complex, and folate are significantly reduced. Rice fortification provides a practical solution by restoring or enhancing these nutrients while maintaining consumer acceptance and traditional eating habits.

Concept of Rice Fortification

Rice fortification is the process of increasing the nutritional value of rice by adding essential micronutrients to rice grains. Fortification may involve adding nutrients to naturally milled rice or producing fortified rice kernels (FRKs) that are blended with regular rice.

The main objective of rice fortification is to provide adequate intake of essential nutrients through a commonly consumed staple food without requiring major changes in dietary patterns.

Nutrients Added During Rice Fortification

Different micronutrients are incorporated depending on the nutritional requirements of the population. Commonly added nutrients include:

Iron: Iron fortification helps prevent iron deficiency anemia, particularly among children, women, and pregnant women. Iron compounds such as ferrous sulfate, ferric pyrophosphate, and elemental iron are commonly used.

Zinc: Zinc plays an important role in immune function, growth, and development. Zinc fortification improves zinc intake among populations with inadequate dietary sources.

Folic Acid: Folic acid is essential for cell division and prevention of neural tube defects during pregnancy.

Vitamin A: Vitamin A fortification helps reduce vitamin A deficiency and supports vision and immune health.

B Vitamins: Thiamine, riboflavin, niacin, and vitamin B₁₂ may be added to improve overall nutritional quality.

Methods of Rice Fortification

Coating Method

In this method, micronutrient premixes are sprayed or coated onto the surface of rice grains using edible materials. The coated rice is then dried and mixed with normal rice.

Advantages:

- ❖ Simple process
- ❖ Low cost
- ❖ Suitable for industrial production

Limitation:

- ❖ Nutrient loss may occur during washing and cooking.

Dusting Method

Micronutrient powders are directly mixed with rice grains. This method is simple but less stable because nutrients can be removed during washing.

Extrusion Technology (Fortified Rice Kernel Production)

Extrusion is the most advanced and widely used technique. Rice flour is mixed with micronutrients and converted into rice-shaped kernels using extrusion equipment. These fortified rice kernels are blended with normal rice.

Advantages:

- ❖ Better nutrient retention
- ❖ Similar appearance and texture to regular rice
- ❖ Higher stability during storage and cooking

Post-Harvest Fortification

Nutrients are added after milling to improve the nutritional profile of polished rice. This method is commonly applied in commercial rice processing.

Production of Fortified Rice Kernels

The production process generally involves:

1. Preparation of rice flour or broken rice
2. Mixing of micronutrient premix
3. Addition of water and binding agents
4. Extrusion into rice-shaped kernels
5. Drying and stabilization
6. Blending with normal rice

The blending ratio of fortified rice kernels usually depends on nutritional requirements and regulatory standards.

Benefits of Rice Fortification

Nutritional Benefits

- ❖ Improves intake of essential vitamins and minerals
- ❖ Helps prevent anemia and micronutrient deficiencies
- ❖ Supports child growth and development

Public Health Benefits

- ❖ Provides nutrition through an affordable staple food
- ❖ Reaches large populations through food distribution programs
- ❖ Reduces health problems related to nutrient deficiencies

Economic Benefits

- ❖ Improves workforce productivity
- ❖ Reduces healthcare costs associated with malnutrition



Fig. 1. Schematic illustration of Rice Fortification

Challenges in Rice Fortification

Consumer Acceptance: Consumers may reject fortified rice due to differences in appearance, color, taste, or texture.

Nutrient Stability: Some vitamins are sensitive to heat, moisture, and storage conditions.

Cost and Technology: Implementation requires appropriate processing technology and quality control systems.

Awareness: Lack of consumer knowledge about fortified foods may affect acceptance.

Future Prospects

- Development of improved extrusion technologies
- Use of bioavailable micronutrient compounds
- Improved sensory quality of fortified rice
- Combination of fortification with biofortification strategies
- Use of smart packaging to maintain nutrient stability

Conclusion

Rice fortification is a promising food-based intervention to address micronutrient deficiencies worldwide. Since rice is consumed daily by a large population, improving its nutritional value can significantly contribute to public health improvement. Advances in extrusion technology and micronutrient delivery systems have improved the feasibility and effectiveness of fortified rice. Proper quality control, consumer awareness, and policy support are essential for successful implementation.

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THE INDISPENSABLE ROLE OF WOMEN IN FORESTRY

Manju Attri*

Ph.D. Scholar, Division of Forest Resource Management, Faculty of Forestry,
Sher-e Kashmir University of Agriculture Sciences and Technology of Kashmir,
Ganderbal, Jammu and Kashmir.

*Corresponding Email: attrimanju24@gmail.com

Abstract

Women are central to forest-dependent livelihoods worldwide, yet they remain persistently underrepresented in forestry policy and governance. The evidence on women's participation in community forestry and conservation, climate adaptation and tenure security, agroforestry and carbon sequestration, and resource collecting and traditional ecological knowledge is compiled in this review. Despite holding less land and fewer formal decision-making positions than men, women are the principal collectors of fuelwood and non-timber forest products, the primary custodians of traditional ecological knowledge, and active participants in community forestry and agroforestry systems. Recent comprehensive assessments demonstrate that gender discrepancies in forest resource access remain structurally entrenched in low- and middle-income countries, despite the fact that women's engagement is increasingly associated with improved governance and conservation outcomes. Thus, as evidence from South Asia, Sub-Saharan Africa, and Southeast Asia shows, secure tenure, participatory governance, and gender-responsive policy are not only issues of equity but also necessary for more resilient communities, healthier forests, and more successful climate outcomes.

Keywords: Women in forestry, Gender and forests, Forest governance, NTFP, Climate change, Tenure rights

Introduction

Forests encompass around 31% of the world's geographical area and support an estimated 1.6 billion people (FAO 2020). Although they have extensive traditional ecological knowledge and gather fuelwood, fodder, and non-timber forest products, women in forest-dependent communities own less land and have fewer formal decision-making positions in forest governance (Agarwal, 2001). Gender equity is acknowledged as crucial to sustainable forest management in international frameworks, such as SDGs 5 and 15 (Larson *et al.*, 2013). A recent systematic analysis of 135 studies reveals that these inequities are caused by gendered patterns of space, labor, and purpose in forest resource use, and that the underlying social norms have remained hard to alter despite decades of policy attention (Bitzer *et al.*, 2024). The policy relevance of going beyond token representation is further highlighted by a review of gender roles and relations in small-scale and community forestry, which reveals that forest outcomes and benefit distribution both improve when women hold substantive rather than nominal positions in governing bodies (Ota *et al.*, 2024). Closing the gap between women's practical contributions and their formal rights and recognition is crucial to sustainable and equitable forest management, according to this paper, which examines evidence on women's contributions to resource collection and traditional ecological knowledge, community forestry and conservation, agroforestry and carbon sequestration, climate adaptation and tenure security.

Resource Collection and Traditional Knowledge

The majority of fuelwood collecting in rural families is done by women and girls, who frequently dedicate several hours a day to the effort (Agarwal, 2001). In communities near forests, non-timber forest products provide for 20–50% of household income, with women handling the majority of gathering and processing (Shackleton & Shackleton, 2004). A study conducted across communities in the Western Ghats revealed that women had much more knowledge of forest plant species than males, indicating that women are often the key holders of traditional ecological knowledge on medicinal plants and seasonal forest change (Gadgil *et al.*, 1993).

Community Forestry and Conservation

According to Agarwal's comparative research of South Asian community forestry, where women actively engaged in governing bodies rather than only nominally, trees regenerated more quickly and benefit distribution was more equal (Agarwal, 2001). Women's involvement in protected-area management committees was linked to higher biodiversity indices and less unlawful extraction, according to a more comprehensive assessment conducted throughout Asia, Africa, and Latin America (Westermann *et al.*, 2005).

Agroforestry and Carbon Sequestration

Women manage the majority of household gardens and multi-strata tree systems, which are among the world's most diverse agroforestry landscapes (Kumar & Nair, 2004). Home gardens can store carbon at levels comparable to some secondary forests, depending on species composition and management (Roshetko *et al.*, 2002). Despite this, there are structural barriers that hinder women from owning trees on land they do not own, such as unstable tree tenure (Fortmann & Bruce, 1988).

Climate Change, REDD+, and Tenure

Climate stressors affecting fuelwood availability, water resources, and food security disproportionately impact women in forest-dependent communities (Hallegatte *et al.*, 2016). Women were largely excluded from the design and benefit-sharing mechanisms of early REDD+ initiatives (Larson *et al.*, 2013). A higher proportion of women in forest management committees increases their participation in decision-making, contributing to improved forest governance and protection (Agarwal, 2010). In much of South Asia and sub-Saharan Africa, women's land rights are often secondary and vulnerable to loss through divorce or widowhood, making secure land and tree tenure a major barrier to equitable resource management (Agarwal, 1994).

Conclusion

Women are fundamental to forestry rather than its periphery. Genuine women's involvement in forest management promotes faster regeneration and more equitable governance. Even though their land rights, decision-making authority, and access to forest finance are still disproportionately restricted, women's labor and leadership consistently support forest health and forest-dependent livelihoods, from fuelwood and non-timber forest product collection to traditional ecological knowledge, community forestry governance, agroforestry, and climate adaptation. Therefore, it is not just an issue of justice but also an ecological and economic need to close the gap between women's contributions and their official rights and acknowledgment. Equal access to carbon funding and REDD+ benefit-sharing, obligatory representation in governance bodies, and gender-responsive tenure reform provide tangible, empirically supported paths toward more sustainable and equitable forests and communities.

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MANAGING BANDED LEAF SHEATH BLIGHT: A GUIDE FOR MAIZE GROWERS

Sunil Kashyap* and Lalit Pal

PAU, Regional Research Station, Gurdaspur

*Corresponding Email: kashyaps@pau.edu

Introduction

Maize is one of the three major staple cereals in the world and third most cultivated cereal after wheat and rice in India. In Punjab state, maize occupied 86.1 thousand hectares, with a production of 370.5 thousand tonnes during 2024-25. The average yield was 43.03 quintal per hectare (17.41 quintal per acre). Hoshiarpur, Rupnagar, Pathankot, Gurdaspur and Amritsar are the leading maize growing districts of the Punjab.

Maize is a multi-purpose crop suitable for food, feed, fodder and industrial use. It is an ideal feedstock for both first- and second-generation biofuel production due to its high starch content and substantial biomass production. It also possesses wide adaptability across diverse agro-climatic conditions, therefore, its demand is growing day by day. This demand can only be fulfilled by increasing the production by growing high yielding cultivars as well as by reducing the losses during the crop production due to various stresses like climatic irregularities and diseases.

Maize is grown in a diverse range of soil and climatic conditions and requires high moisture and warmth during its life cycle. These growth conditions favour many disease and pest infestation in Maize. Seed rot and seedling blight, banded leaf and sheath blight, maydis leaf blight, bacterial stalk rot, post-flowering stalk rot and brown stripe downy mildew are the important diseases of maize prevalent in Punjab conditions. Out of these, banded leaf and sheath blight (BLSB) rapidly gained economic interest recently due to its potential to cause complete crop loss. This destructive disease caused by fungal pathogen *Rhizoctonia solani* f.sp. *sasakii* leads to significant reduction in yield of maize crop in Punjab, India. The pathogen is very prevalent in humid weather (with 90-100 per cent relative humidity) and the temperature around 28 to 30°C.

BLSB was first documented in 1927 by Bertus in Ceylon (present-day Sri Lanka), where it was described as a sclerotial disease. In India, the disease was later reported from the Tarai region of Uttar Pradesh (now Uttarakhand) by Payak and Renfro in 1966. During the early 1970s, BLSB reached epidemic proportions in the warm foothill regions of Mandi district, Himachal Pradesh, highlighting its increasing threat to maize cultivation.

Over the years, the disease has been referred to by several names, including ear rot, sheath blight, banded sclerotial disease, banded sheath rot, and horizontal banded blight. Today, BLSB is widely prevalent across the major maize-growing regions of India. It affects the crop throughout its growth cycle—from the seedling stage to cob development—making it one of the most important diseases limiting maize productivity. Under severe disease pressure, particularly when the ear rot phase becomes dominant, Banded Leaf Sheath Blight (BLSB) can cause yield losses of up to 100%. In Punjab, prolonged spells of high humidity and heavy rainfall during the monsoon months of July and August create highly favourable conditions for disease development and rapid spread, leading to significant damage in susceptible maize crops if timely management practices are not adopted.

This disease poses a great challenge to the maize farmers because it is very difficult to control through fungicides due to its soil borne nature. This disease spreads through irrigation water, flooding or through the transport of contaminated soil in farm implements.

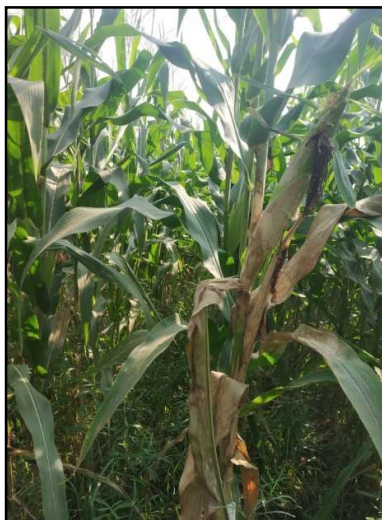
Sign and symptoms the Disease:

BLSB affects almost all above-ground parts of the maize plant, except the tassel. The disease typically begins as small, water-soaked, straw-coloured lesions on the lower leaf sheaths near the soil surface. As the infection progresses, these lesions become necrotic and develop characteristic alternating light and dark brown bands. Over time, neighbouring lesions enlarge and merge, forming extensive blighted areas.

Under natural field conditions, BLSB usually appears during the pre-flowering stage, although young plants may also become infected under favourable environmental conditions, leading to severe blighting and substantial yield losses. The disease initially infects the leaf sheaths and leaf blades that come into contact with the soil. It then spreads upward from the sheaths to the lower leaves, where lesion expansion is more rapid and extensive.

As the infection advances, the pathogen invades the stalk beneath the affected sheaths, producing elongated dark brown lesions on the rind. These lesions gradually coalesce, covering large portions of the internodes. The disease may further spread to the ears, husks, silks, and developing kernels. In the later stages, numerous brown sclerotia—the survival structures of the fungus—are formed on the leaf sheaths, husks, and cobs.

Infected kernels often become shrivelled, discoloured, and smaller than normal due to fungal colonization. The ears turn brown, and under severe infection, premature drying and cracking of the husks can completely destroy the developing cobs, resulting in significant losses in both grain yield and quality.

Management of Banded Leaf Sheath Blight

Symptoms of the Disease Sclerotia formation on stem

Managing Banded Leaf Sheath Blight (BLSB) is challenging because the causal fungus survives in the soil for long periods and infects a wide range of host plants. This broad host range limits the effectiveness of crop rotation as a disease management strategy. Furthermore, the lack of

commercially available maize hybrids with reliable resistance makes integrated disease management essential.

According to the recommendations of Punjab Agricultural University (PAU), timely fungicide application can effectively suppress disease development. Spraying Amistar Top 325 SC (Azoxystrobin 18.2% + Difenoconazole 11.4% SC) at a dose of 100 ml per acre mixed in 200 litres of water should be carried out as soon as the initial symptoms appear. If favourable weather conditions persist or disease symptoms continue to develop, a second spray may be applied after an interval of 15 days.

In addition to fungicide use, several cultural practices help reduce disease incidence. Farmers should remove infected crop residues after harvest to minimize the build-up of the pathogen in the field. Maintaining the recommended plant spacing improves air circulation within the crop canopy, thereby reducing humidity around the plants. Removing the lower leaves that come in contact with the soil can also limit the spread of the pathogen from the soil to the upper parts of the plant. Adopting these practices together as part of an integrated disease management approach provides more effective and sustainable control of BLSB.

Conclusion

Banded Leaf Sheath Blight, caused by the soil-borne fungus *Rhizoctonia solani* f. sp. *sasakii*, has emerged as one of the major constraints to profitable maize production. The disease can infect the crop from the seedling stage to cob maturity and is particularly severe under warm, humid conditions, dense crop stands, and excessive nitrogen fertilization. Prolonged leaf wetness due to rainfall or irrigation further favours disease development and spread.

Since complete control through a single method is not possible, successful management relies on an integrated approach that combines field sanitation, proper crop management, regular field monitoring, and timely fungicide application. By adopting these recommended practices, maize growers can substantially reduce disease severity, safeguard grain yield and quality, and improve the overall profitability of maize cultivation.

DATA AS BACKBONE: THE ROLE OF BIG DATA IN BUILDING VIKSIT BHARAT**Moumita Baishya^{1*}, Nobin Chandra Paul² and Saista Tabssum¹**¹Deptt. of Statistics & Computer Applications,

Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar-848125

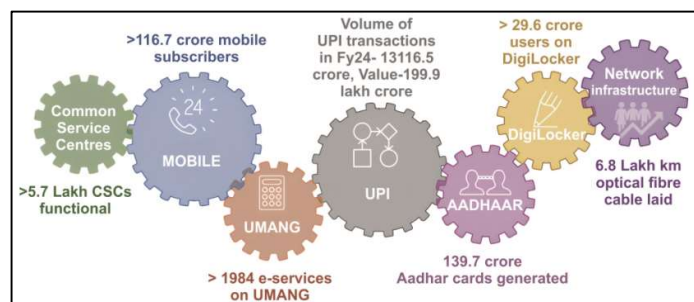
²ICAR- National Institute of Abiotic Stress Management, Baramati, India,*Corresponding Email: moumitabaishya102@rpcau.ac.in**Abstract**

The dream of a Viksit Bharat is not only about achieving economic growth but also about building a nation that makes informed, timely, and inclusive decisions. In today's digital era, data has emerged as one of the country's most valuable resources. From digital payments and satellite imagery to healthcare records and agricultural databases, India generates enormous amounts of information every day. When analysed using statistical methods and artificial intelligence, this vast pool of data has the potential to transform governance, strengthen public services, and improve the quality of life of citizens. This article discusses how Big Data is becoming a key driver in India's development journey by supporting evidence-based policymaking and proactive governance. It highlights the role of Big Data in important sectors such as agriculture, healthcare, and urban planning, where data-driven insights help improve efficiency, transparency, and decision-making. The article also emphasizes the importance of combining statistical rigor with responsible and explainable AI to ensure reliable outcomes. At the same time, it addresses critical challenges related to data privacy, digital inequality, bias, and institutional capacity. The article concludes that when used ethically and responsibly, Big Data can become a powerful foundation for building an inclusive, resilient, and developed India.

Keywords: Big Data, Viksit Bharat, Artificial Intelligence, Digital Governance, Evidence-based Decision Making, Inclusive Development.

Introduction

India's journey to Viksit Bharat is not merely about bigger plans, it is about better decisions. In a nation of more than 1.4 billion people, the scale and complexity of governance demand that policy choices be anchored in evidence. In recent years we have gathered, often without noticing, a tremendous resource called data. When harnessed thoughtfully combined with sound statistics and responsible AI; Big Data can become the backbone of development, turning policy from reactive patchwork into proactive design.

**Fig 1: India's Digital Public Infrastructure (Economic Survey, 2023-2024)**

Understanding Big Data in the Indian Context

Big Data refers to datasets characterised by large in scale, speed, and diverse in variety, generated from sources such as digital payments, satellite systems, administrative records, sensors, and mobile platforms. India's rapid digitalisation has significantly expanded such data sources. Digital public infrastructure initiatives like digital identity systems, electronic service delivery platforms, and open government data portals generate massive streams of information daily. According to global estimates, the world generates over 2.5 quintillion bytes of data per day, and India is now one of the fastest-growing contributors to this digital universe. Administrative data is often not designed for inference and may reflect access biases. Statistics plays a crucial role in cleaning, validating, and calibrating such data so that conclusions drawn from it are reliable and representative.

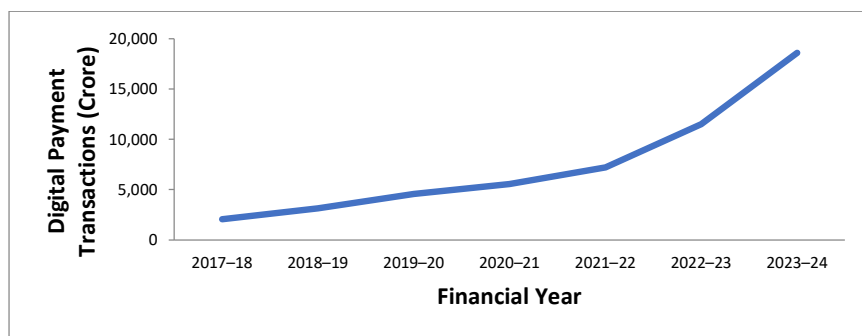


Fig 2: Growth of Digital Payment Transaction in India (PIB 2018–2024, Ministry of Finance, GoI)

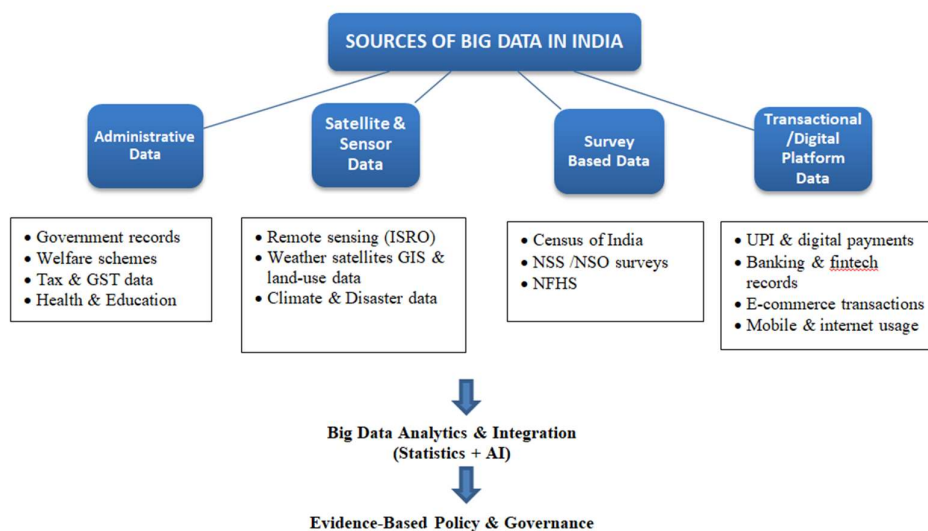


Fig 3: Sources of Big Data in India

Big Data in Governance: From Reactive to Proactive Administration

One of the most significant contributions of Big Data to Viksit Bharat lies in governance. Traditional governance systems relied on periodic reports and delayed feedback. Today, real-time dashboards powered by Big Data allow continuous monitoring of public programs. For example, digital service delivery platforms enable ministries to track benefit transfers, identify delays, and reduce leakages in welfare schemes. Big Data analytics allows governments to shift

from reactive governance responding after problems arise to predictive governance, where potential issues are identified early. Statistical models help measure performance and outcomes, while AI algorithms detect patterns, anomalies, and emerging risks. As a result, public resources are allocated more efficiently and equitably.

Sectorial Applications: Health, Agriculture, Urban Development

Big Data's potential is felt across sectors. In health, integrating hospital records, surveillance data and demographic profiles permits targeted screening and rational allocation of beds and vaccines. In agriculture, satellite imagery combined with weather models and local market prices supports early yield forecasting and advisories vital for a sector that still employs over 40% of India's workforce and for which timely information affects incomes directly (World Bank, 2024 & MoSPI, GoI, 2024). In cities, mobility and pollution sensors inform routing, public transport planning and sanitation deployment. When forecasts are probabilistic rather than single-point guesses communicating a range of likely outcomes governments can plan buffer stocks and procurement with less fiscal panic and more confidence. In agriculture, Big Data combined with remote sensing and weather data supports crop monitoring, yield prediction, and market intelligence. This is particularly important as agriculture still employs over 40% of India's workforce, making data-driven decision support essential for food security and farmer welfare. In urban planning, mobility data, pollution sensors, and satellite imagery support smarter transport systems, waste management, and environmental monitoring.

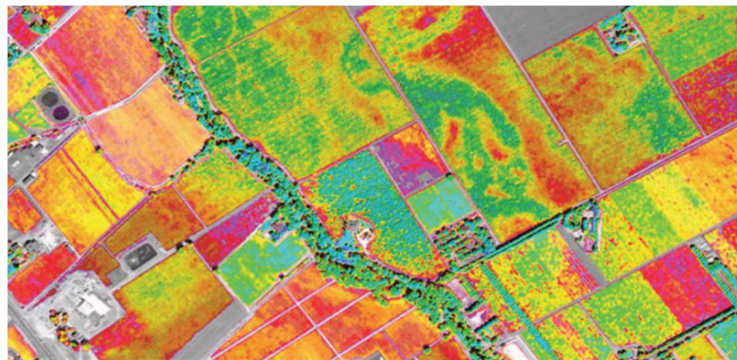


**Fig 4: Satellite-based monitoring of crops or urban infrastructure
(NASA-ISRO NISAR mission, 2025)**

Role of Statistics and AI in Big Data ecosystem:

Statistics and artificial intelligence play complementary roles in the Big Data ecosystem. Statistics ensures scientific sampling, bias correction, uncertainty measurement, and causal interpretation. AI enhances scale and speed by analysing complex, high-dimensional datasets and generating predictive insights. However, AI models are only as good as the data and assumptions underlying them. Without statistical validation, AI risks becoming a black box that amplifies existing inequalities. "Big data gives small signals a powerful voice, but only when interpreted correctly" (Kitchin, 2014). Therefore, Big Data systems for Viksit Bharat must be built on strong statistical foundations and transparent and explainable AI models.

Challenges: Privacy, Bias, and Digital Divide

Despite its immense potential, Big Data also presents serious challenges that must be addressed with care and foresight. In a democratic society, data privacy, security, and ethical use are

fundamental concerns, particularly when large volumes of personal and administrative data are involved. Many administrative and digital datasets, while extensive, may unintentionally exclude digitally marginalised populations, leading to conclusions that reflect patterns of access rather than actual need. If left unchecked, algorithmic decision-making can therefore reinforce existing inequalities instead of correcting them. To prevent this, data systems must be designed to protect informed consent, minimise the risk of re-identification, and ensure that algorithmic decisions are transparent, explainable, and open to challenge (Floridi *et al.*, 2018). Beyond ethical safeguards, three practical constraints demand attention. First, representativeness remains a persistent issue, as digital records often under-capture rural communities, informal workers, and small farmers. Second, institutional capacity is uneven, with many local and district-level agencies lacking the technical expertise required to interpret analytics and convert insights into timely action. Third, governance and coordination continue to pose challenges, as effective data sharing across departments depends on interoperable standards, clear legal safeguards, and well-defined accountability mechanisms. While India has begun strengthening its data protection and governance frameworks, sustaining these efforts through continuous oversight and capacity building will be essential to ensure that Big Data serves inclusive, fair, and trustworthy development.

Conclusions

Big Data can serve as the backbone of Viksit Bharat only when used responsibly, ethically, and scientifically. Statistics provides reliability, AI provides scalability, and governance provides accountability and together they transform raw data into meaningful insights that improve lives. When data systems are made keeping people's needs in mind, Big Data becomes more than just a computer tool; it becomes a powerful resource for the whole nation. In agriculture, when farmers receive timely information about weather, crops, and market prices, it helps them improve production, avoid losses, and protect their livelihoods. India's challenge is not data scarcity, but ensuring that data serves development with fairness, transparency, and trust.

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**BIOCHAR IN PLANT DISEASE MANAGEMENT: AN
ECO - FRIENDLY APPROACH TO MANAGING PHYTOPATHOGENS**

**Shruti Sinha¹, Akoijam Ratankumar Singh², Om Prakash^{1*},
Anjali Kumari Jha³, Rishav Kumar¹, Dhanraj Kumar¹**

¹College of Agriculture, Iroisemaba- 795004 Central Agricultural University (Imphal), Manipur

²ICAR-Research Complex for North Eastern Hill Region,

Manipur Centre, Lamphelpat, Imphal West, 795004, Manipur, India

³Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal

*Corresponding Email: omprakash.nayaganj@gmail.com

Abstract

Biochar, as a multifunctional soil conditioner has demonstrated significant potential for sustainable plant disease suppression. Its primary role in disease management involves regulating soil microbial communities and promoting beneficial microorganisms. Biochar, a charcoal-like material, offers an eco-friendly approach to managing phytopathogens. It is produced by heating plant materials and agricultural waste under oxygen-limited conditions, typically at high temperatures (250-700°C). Biochar is also an effective carbon-sequestering material and plays an important role in improving soil health and mitigating environmental pollution. The major benefits of biochar is its ability to suppress plant pathogens by modifying soil physical and chemical properties, stimulating beneficial and antagonistic microorganisms, and enhancing plant defence mechanisms. However, the disease-suppressive efficacy of biochar is influenced by several factors, including feedstock type, preparation conditions, application practices, and the types of plants and pathogens involved. This article explores how these factors influence disease suppression, particularly through their effects on soil microbial communities.

Keywords: Biochar, Soil amendment, Phytopathogens, Diseases management, Agrochemicals.

Introduction

As the demand for safe and sustainable food production continues to grow, farmers are increasingly seeking practical ways to protect crops without harming the environment. Modern agriculture faces several challenges, including declining soil health, increasing plant diseases, reduced crop quality, and yield losses. Although chemical pesticides have played an important role in disease management, their repeated and long-term use can cause environmental pollution, soil degradation, loss of beneficial microorganisms, and the development of pesticide-resistant pathogens. Therefore, sustainable and environmentally friendly approaches are urgently needed to improve soil health and reduce crop losses. In this context, soil amendments, particularly organic amendments, have emerged as promising strategies for enhancing plant health and managing diseases. Among these, biochar has gained considerable attention because of its potential to suppress plant pathogens and improve soil functionality.

Biochar is a stable, carbon-rich material produced by heating plant or agricultural waste under oxygen-limited conditions. It improves soil structure, enhances water and nutrient retention, and supports beneficial microorganisms. By creating a healthier soil environment, biochar can suppress various plant diseases and reduce dependence on chemical pesticides. It can act directly by inhibiting pathogens and indirectly by strengthening plant defence mechanisms. Moreover,

combining biochar with beneficial microbes such as *Trichoderma*, *Bacillus*, and *Pseudomonas* can enhance their colonization, persistence, and antagonistic activity in the rhizosphere, further improving disease suppression.

Biochar preparation: The effectiveness of biochar in managing plant diseases mostly depends on how it is produced. The type of raw material used, such as crop residues, wood, or other agricultural wastes (feedstock), and the temperature at which it is produced through pyrolysis determine its key properties, including pore structure, pH, and carbon content. These characteristics directly influence the ability of biochar to suppress plant diseases and promote plant health.

i. Feedstock material: Feedstock is the raw material used to produce biochar through pyrolysis, a heating process with limited or no oxygen. The type of feedstock strongly influences biochar properties and disease-suppressive ability of biochar. Common feedstocks include crop residues such as wheat, maize, and tobacco straw, wood, and greenhouse waste. Straw-based biochar is widely used because residues are readily available and recyclable in agricultural fields. Greenhouse waste biochar, rich in nitrogen and phosphorus, promotes plant growth and disease resistance. Straw biochar improves soil health, supports beneficial microorganisms, and strengthens plant tissues through its silicon content. Wood biochar, with its high porosity, can adsorb harmful compounds released by pathogens. Thus, selecting suitable feedstock is essential for effective plant disease management.

ii. Pyrolysis Temperature: It is a key factor determining the effectiveness of biochar in plant disease management. Biochar can be produced through methods such as fast, slow, flash, vacuum, hydrothermal, intermediate, and microwave-assisted pyrolysis, as well as torrefaction, flash carbonization, hydrothermal carbonization, and gasification. Temperatures generally range from 250–700°C, with 350–550°C often considered suitable for disease suppression. Temperature alters biochar's physicochemical properties, porosity, nutrient availability, and interactions with microorganisms. Higher temperatures increase aromatic carbon structures and pore development, providing greater surface area for microbial colonization. However, excessive temperatures above 550°C may reduce surface area and microbial habitats. For example, straw biochar produced at 400°C showed an optimal pore structure that supported dense microbial colonization. Pyrolysis also releases volatile organic compounds that may suppress pathogens but can sometimes cause phytotoxicity. High temperatures above 500°C improve phosphorus retention but may reduce its availability to plants. Therefore, pyrolysis temperature should be optimized according to the intended application and disease-management objectives.

iii. Biochar modifications: Biochar-mediated disease suppression can be enhanced through targeted modification. During pyrolysis, the loss of pores and functional surface properties may reduce its efficacy. Activation strategies, such as chitosan coating, improve the adsorption of harmful compounds and support root health, while

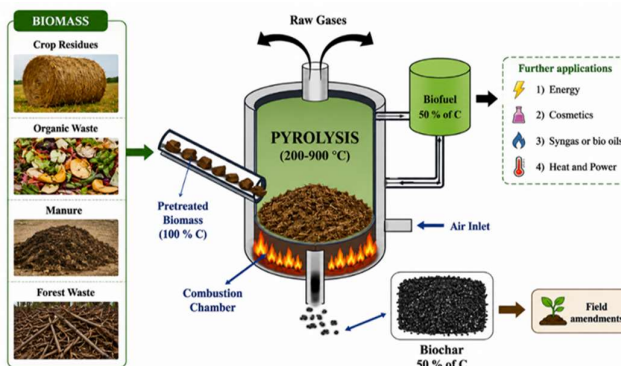


Fig 1. Production technique of Biochar (Dorjee *et al.*, 2023)

silica modification enhances beneficial microbial populations and suppresses phytopathogens. Furthermore, integrating biochar with biocontrol agents, including *Bacillus*, *Trichoderma*, and *Chaetomium*, represents a promising approach for sustainable disease management. The porous structure of biochar provides a favorable habitat that enhances microbial survival and colonization. These beneficial microorganisms suppress pathogens through competition and antagonism while stimulating plant defense responses, thereby improving soil health, microbial diversity, and crop productivity.

Biochar Applications: The effectiveness of agricultural inputs relies heavily on their delivery methods and dosage. Biochar can be integrated into fields through several established techniques, such as broadcasting, deep banding, spot placement, tractor-propelled spreading, or co-application with compost and manure. Research indicates that an application rate of 10-20 t/ha can elevate the plant photosynthetic rate by 25%, and combining a higher rate of 50 t/ha

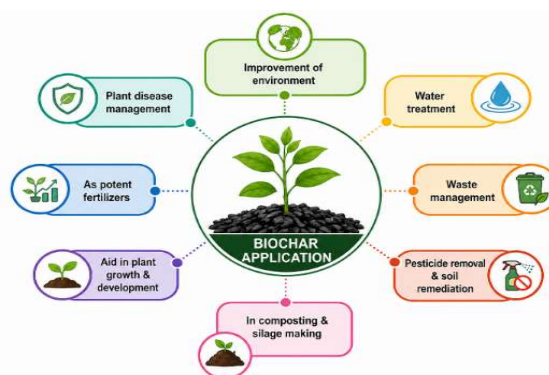


Fig. 2. Biochar Application (Zhang *et al.*, 2026)

with cattle manure up to 58% , in maize yields. Biochar is an important soil amendment that improves soil fertility, water and nutrient retention, and overall soil health. Its stable carbon content also contributes to climate change mitigation through long-term carbon storage. Due to its porous structure and large surface area, biochar improves the physical, chemical, and biological properties of soil, particularly with long-term application, thereby promoting crop growth and productivity. It can also adsorb and immobilize soil contaminants such as herbicides, pesticide residues, heavy metals, metalloids, and emerging pollutants like microplastics, improving soil quality and environmental safety. Altogether, biochar supports sustainable agriculture by enhancing soil health, ecological functioning, and resource retention. Beyond agriculture, biochar can be used for renewable energy production through combustion and in advanced applications such as lithium-ion batteries and graphene production due to its high surface area and electrical conductivity.

Biochar application factors: The effectiveness of biochar in controlling plant diseases depends on several factors, including environmental conditions, application rate, land management practices, and interactions between the host plant and pathogen.

i. Environmental conditions strongly influence biochar performance: Disease suppression is generally higher in pot or greenhouse experiments (48.09% - 93.52%) than in field conditions (7.37% -77.32%), where weather, soil, season, and pathogen spread cause greater variability. Biochar often performs better in soils with low organic matter, while its benefits may be limited in organic-rich soils.

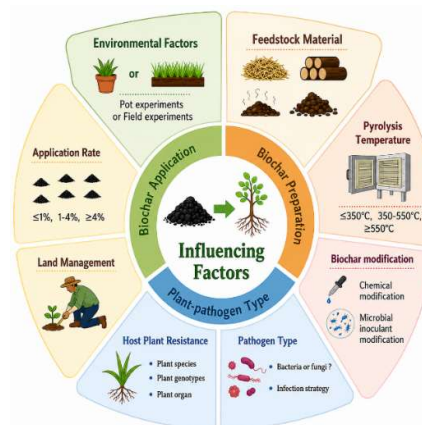


Fig. 3. Influencing factor of Biochar Application (Zhang *et al.*, 2026)

ii. Application rate of biochar:

Biochar shows an inverted U-shaped response, with disease suppression increasing up to an optimum rate and declining at excessive levels. Generally, 1- 4% (w/w) is effective, with 2% showing maximum suppression in some studies. Moderate rates improve nutrient availability and beneficial microbial activity, whereas excessive amounts may bind nutrients and reduce microbial growth. Thus, the optimum rate should be tailored to the crop and soil.

iii. Land management practices - It can further enhance biochar effectiveness, combining biochar with appropriate nitrogen management can maintain soil microbial diversity, while biochar-compost mixtures can reduce disease and improve crop yield. Adding 1% biochar can also shorten fertilizer pre-treatment time from 45 days to 10-14 days while maintaining 85% disease control.

Plant-Pathogen Interactions: Biochar effectiveness varies with pathogen type, host genotype, plant part, and mode of infection. Reported suppression rates are 86% for fungi, 96% for bacteria, 100% for oomycetes and viruses, and 50% for nematodes. Therefore, biochar application should be tailored to specific crops, soils, pathogens, and management conditions. For example, 110 kg/ha reduced *Fusarium* abundance in *Panax pseudoginseng* root rot, whereas 80 kg/ha was more effective against *Ilyonectria* causing yellow rot.

Conclusion and Future prospect

Biochar represents a promising and sustainable approach for integrated plant disease management, offering the dual benefits of improving soil health and enhancing plant resilience. Its disease-suppressive effects are mediated through multiple mechanisms such as modification of soil physicochemical properties, adsorption of phytotoxic compounds, stimulation of beneficial microorganisms, and activation of plant defence responses. However, its efficacy is highly variable and depends on feedstock characteristics, pyrolysis conditions, application rate, soil properties, environmental factors, and pathogen interactions. Research focusing on the integration of biochar with compost, fertilizers, and biological control agents through long-term field evaluations could provide practical benefits to farmers and promote sustainable agricultural production. Such integrated approaches may enhance disease suppression, improve soil fertility and crop productivity, and strengthen climate resilience, thereby supporting sustainable and environmentally friendly crop production.

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BIOFERTILIZERS: NATURE'S SOLUTION TO SOIL FERTILITY**Shruthi, G. S¹ and Supriya, M. E²**

¹ Senior Research Fellow, All India Co-ordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants, Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, GKVK, Bengaluru-560065

² Assistant Professor, Department of Soil Science and Agricultural Chemistry, GPS Institute of Agricultural Management, Peenya 1st Stage, Bengaluru, Karnataka, India

*Corresponding Email- shruthigowda1997@gmail.com

Abstract

Biofertilizers are sustainable agricultural inputs containing beneficial microorganisms that improve soil fertility, nutrient availability and plant growth. Microbes such as *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria and mycorrhizal fungi enhance nutrient cycling, promote crop productivity and support soil health through biological processes. They reduce dependence on chemical fertilizers and contribute to environmentally friendly and sustainable agriculture. Despite challenges in quality control and adoption, biofertilizers have great potential for improving soil conservation and future food security.

Keywords: Biofertilizers; soil fertility; beneficial microorganisms; nutrient cycling; sustainable agriculture.

Introduction

Soil is the foundation of agricultural production, providing nutrients, water and support for plant growth. However, intensive farming, continuous cultivation and excessive use of chemical fertilizers have resulted in soil degradation, nutrient imbalance and reduced biological activity (Lal, 2015). These challenges have increased the need for sustainable nutrient management practices. Biofertilizers are microbial inoculants containing beneficial microorganisms that enhance soil fertility and plant growth through processes such as nitrogen fixation, phosphorus solubilization, nutrient mobilization and production of plant growth promoting substances. Microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria, arbuscular mycorrhizal fungi (AMF) and cyanobacteria improve nutrient availability, enhance root growth and increase crop productivity (Richardson *et al.*, 2009). Unlike chemical fertilizers, biofertilizers promote natural nutrient cycling, improve soil microbial diversity and support long-term soil health with fewer environmental impacts. Their integration with organic amendments and balanced fertilization contributes to sustainable crop production and improved nutrient-use efficiency (Bhattacharyya & Jha, 2012).

With growing concerns about climate change, soil degradation and food security, biofertilizers offer an eco-friendly approach for maintaining soil fertility and agricultural sustainability. This article highlights their role, mechanisms, benefits, application methods, challenges and future prospects.

Definition of Biofertilizers

Biofertilizers are preparations containing beneficial microorganisms that improve soil fertility and plant growth by enhancing nutrient availability through biological processes such as nitrogen fixation, phosphorus solubilization, nutrient mobilization and production of plant growth-

promoting substances (Vessey, 2003). Unlike chemical fertilizers, they do not directly supply nutrients but improve soil microbial activity and nutrient-use efficiency.

Important biofertilizer microorganisms include *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria (PSB), potassium-solubilizing microorganisms, arbuscular mycorrhizal fungi (AMF) and cyanobacteria, which enhance nutrient cycling, soil microbial diversity and long-term soil fertility (Richardson *et al.*, 2009).

Nature's Tiny Helpers: Beneficial Microorganisms in Biofertilizers

1. *Rhizobium*

Rhizobium forms root nodules in leguminous crops such as soybean, chickpea, pea and groundnut, where it fixes atmospheric nitrogen into plant-available forms, reducing the need for synthetic nitrogen fertilizers (Vessey, 2003).

2. *Azotobacter*

Azotobacter is a free-living nitrogen-fixing bacterium that improves soil fertility and produces plant growth-promoting substances such as IAA, gibberellins and siderophores, which enhance root growth and nutrient uptake (Bhattacharyya & Jha, 2012).

3. *Azospirillum*

Azospirillum associates with the roots of cereals and grasses such as rice, wheat, maize and sugarcane. It improves root development, nutrient absorption and plant tolerance to environmental stresses (Bhattacharyya & Jha, 2012).

4. Phosphate-Solubilizing Bacteria (PSB)

PSB, including *Bacillus* and *Pseudomonas* species, release organic acids and enzymes that convert unavailable soil phosphorus into plant-available forms, improving phosphorus-use efficiency and crop growth (Richardson *et al.*, 2009).

5. Arbuscular Mycorrhizal Fungi (AMF)

AMF form symbiotic associations with plant roots and enhance the uptake of phosphorus, micronutrients and water through their extensive fungal networks. They also improve soil structure and plant tolerance to stress.

6. Cyanobacteria

Cyanobacteria such as *Anabaena* and *Nostoc* fix atmospheric nitrogen and are especially useful in rice ecosystems, where they improve soil nitrogen status and biological activity.

How Do Biofertilizers Work?

1. Nitrogen Fixation

Nitrogen-fixing microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum* and cyanobacteria convert atmospheric nitrogen into plant-available forms through the enzyme nitrogenase. This process improves soil nitrogen status and reduces dependence on synthetic nitrogen fertilizers (Glick, 2012).

2. Phosphorus Solubilization

Phosphate-solubilizing bacteria (PSB), including *Bacillus* and *Pseudomonas*, release organic acids and enzymes that convert unavailable phosphorus into forms accessible to plants. This enhances phosphorus uptake, root growth and crop productivity (Richardson *et al.*, 2009).

3. Nutrient Mobilization

Arbuscular mycorrhizal fungi (AMF) and other beneficial microbes improve the uptake of phosphorus, micronutrients, potassium and water by extending the root absorption area. They also enhance nutrient-use efficiency and plant tolerance to environmental.

4. Production of Plant Growth-Promoting Substances

Many biofertilizer microorganisms produce growth-promoting compounds such as indole-3-acetic acid (IAA), gibberellins, cytokinins, siderophores and ACC deaminase, which stimulate root development, improve nutrient uptake and increase plant resilience (Bhattacharyya & Jha, 2012).

Benefits of Biofertilizers for Soil and Crops

1. Improved Soil Health

Biofertilizers increase beneficial microbial populations, improve nutrient cycling, organic matter decomposition, soil structure and water-holding capacity. They also support a healthier soil environment by promoting microbial diversity and reducing the impact of some soil-borne pathogens.

2. Enhanced Nutrient Uptake

Microorganisms involved in nitrogen fixation, phosphorus solubilization, potassium mobilization and mycorrhizal associations improve the availability and uptake of essential nutrients. Their activities increase nutrient-use efficiency and reduce nutrient losses (Richardson *et al.*, 2009).

3. Stronger Root Systems

Biofertilizer microorganisms produce plant growth-promoting substances such as IAA, gibberellins and cytokinins that stimulate root growth and improve plant development. Stronger root systems enhance nutrient and water absorption and increase stress tolerance (Bhattacharyya & Jha, 2012).

4. Higher Yield and Reduced Fertilizer Costs

Improved nutrient availability and plant growth lead to better crop yield and quality. Biofertilizers can partially replace chemical fertilizers by supplying nutrients naturally, reducing input costs and minimizing environmental pollution.

Choosing the Right Biofertilizer

The effectiveness of biofertilizers depends on selecting suitable microorganisms according to crop type, soil conditions, climate and farming system. *Rhizobium* is mainly used for leguminous crops, while *Azotobacter* and *Azospirillum* are beneficial for cereals, vegetables and horticultural crops. Phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) improve phosphorus and micronutrient availability (Vessey, 2003; Richardson *et al.*, 2009). Soil factors such as pH, moisture, organic matter and microbial activity influence their performance. Combining biofertilizers with organic amendments and balanced fertilization improves their effectiveness (Bhattacharyya & Jha, 2012).

Best Practices for Successful Use of Biofertilizers

Common methods include seed treatment, seedling root dipping and soil application. Seed treatment helps establish beneficial microbes near young roots, while root dipping improves microbial colonization in transplanted crops. Soil application with compost or farmyard manure supports microbial survival and activity (Vessey, 2003).

Challenges and Future Opportunities

Despite their benefits, biofertilizers face challenges such as inconsistent product quality, limited farmer awareness, poor storage facilities and improper application practices. Advances in

microbial biotechnology and development of multifunctional microbial consortia offer opportunities to improve their efficiency and field performance (Glick, 2012). Stronger quality standards, farmer training and policy support are essential for wider adoption.

Conclusion

Biofertilizers are a sustainable tool for improving soil fertility, nutrient availability, crop productivity and environmental health. Beneficial microorganisms enhance nutrient cycling, strengthen plant growth and support long-term soil quality while reducing dependence on chemical fertilizers. Although challenges such as quality control and farmer awareness remain, advances in microbial technology and better management practices can increase their adoption. Biofertilizers will play an important role in sustainable agriculture, soil conservation and future food security.

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CLIMATE SMART AGRICULTURE: A SUSTAINABLE APPROACH FOR FUTURE FARMING

Ananya Tiwari^{1*}, Rajat yadav², Suryabhan³ and Dipake Shital⁴

¹Phd, Department of Agricultural Biochemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur 208002, (U.P.)

²Phd, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur 208002, (U.P.)

⁴Phd, Department of Plant Pathology, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur 208002, (U.P.)

⁴Chandra Shekhar Azad University of Agriculture and Technology, Kanpur 208002, (U.P.)

³rd SRF, ICAR- Indian Institute of Pulses Research, Kanpur 208024, (U.P.)

*Corresponding Email: ananya23tiwari@gmail.com

Abstract

The Climate-Smart Agriculture concept that promotes food security, sustainable livelihoods and climate resilience and greenhouse gas mitigation. Agriculture produces approximately 21.9% of global GHG emissions, but food production must increase by 50-60% to meet the demands of an expected 9.7 billion people by 2050. The major CSA practices can boost productivity by 10–30%, reduced production costs by 15–40%, increase water- use efficiency by 20 - 35%, promote carbon sequestration and mitigate climate-related yield losses. In India, where approximately 52% of agricultural land relies on rainfall and nearly 46% of the workforce is engaged in the agricultural sector, while climate-smart agriculture has the potential to enhance resilience and livelihoods, its adoption is hindered by significant barriers, including high investment costs, restricted access to technology, limited awareness and a shortage of climate-resilient crop varieties.

Keywords: Conservation agriculture, climate resilience crops, diversification, mitigation.

Introduction

Climate-smart agriculture (CSA) is an integrated framework for managing agricultural systems to tackle the dual challenges of food security and climate change. Its core objectives are to sustainably boost agricultural productivity and income, strengthen resilience and adaptation to climate change, and minimize or eliminate greenhouse gas emissions where feasible. By its nature, CSA is context-specific, drawing on a diverse range of technologies, policies, institutions, and investments at both the farm level and beyond. It focuses on balancing the synergies and trade-offs between productivity, adaptation, and mitigation across the entire agri-food system (FAO, 2021). It is based on three main objectives: Increasing agricultural productivity and income, Enhancing resilience (adaptation) to climate change and reducing greenhouse gas emissions (mitigation).

Key Practices of Climate-Smart Agriculture

- (1) Crop Diversification: Growing two to four crops annually instead of a single crop reduces production risk.
- (2) Conservation Agriculture: Minimum or zero tillage, Crop residue retention
- (3) Drip irrigation and Rainwater harvesting
- (4) Climate-Resilient Crop Varieties
- (5) Agroforestry



Benefits for Farmers

Adoption of Climate-Smart Agriculture provides measurable economic and environmental benefits:- 10–30% higher crop productivity under improved management. 15–40% reduction in production costs through efficient use of water, fertilizers, and fuel. 20–35% improvement in water-use efficiency. 15–30% increase in soil organic carbon, improving long-term soil fertility. 20–50% reduction in yield losses during droughts and floods. 15–40% increase in net farm income through diversified and sustainable farming systems etc.

Economic and Environmental Importance

Climate-Smart Agriculture plays a crucial role in ensuring food security while conserving natural resources. Agriculture contributes approximately 22% of global greenhouse gas emissions. Sustainable farming practices can reduce agricultural emissions by 10–25%. Conservation agriculture can lower soil erosion by up to 90%. Agroforestry can store 30–300 t carbon ha⁻¹ over its lifetime. Integrated nutrient and water management can improve nutrient-use efficiency by 20–40%. Biodiversity in diversified farming systems can increase by 15–30%.

Challenges in Adoption

Despite its proven benefits, CSA adoption remains limited due to several constraints: Only 25–35% of smallholder farmers have access to modern climate-smart technologies. Initial investment costs for drip irrigation and precision farming may range from ₹40,000 to ₹80,000 per hectare. Less than 40% of farmers regularly receive reliable climate advisory services. Limited availability of climate-resilient seed varieties in many regions. Inadequate infrastructure, extension services, and policy support.

Future Scenarios

The importance of Climate-Smart Agriculture will continue to increase as climate risks intensify. Global food demand is expected to rise by 50–60% by 2050. Extreme weather events are projected to increase in both frequency and intensity. Digital agriculture technologies, including AI, IoT, drones, remote sensing, GIS, and weather forecasting, can improve resource-use efficiency by 15–30%. Precision agriculture has the potential to reduce fertilizer use by 10–20% while increasing

productivity by 10-15%. Expansion of CSA practices could significantly improve national food security while reducing agriculture's environmental footprint.

Conclusion

Climate-Smart Agriculture is a scientifically proven and sustainable approach for addressing the dual challenges of climate change and food security. By adopting CSA practices, farmers can achieve 10-30% higher productivity, 15-40% higher income, 30-60% water savings, and 10-25% lower greenhouse gas emissions while enhancing resilience against climate extremes. Strengthening farmer awareness, expanding access to climate-smart technologies, increasing policy support, and promoting digital agriculture will be essential for large-scale adoption. Climate-Smart Agriculture offers a practical pathway toward resilient, productive, and environmentally sustainable farming systems for the future.

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SUPERFRUIT UNDER SIEGE: TOP PESTS AND DISEASES THREATENING DRAGON FRUIT

Om Prakash¹, A. Ratankumar Singh², Shruti Sinha^{1*}, Anjali Kumari Jha³,
Rishav Kumar¹ and Dhanraj Kumar¹

¹College of Agriculture, Iroisemaba- 795004

Central Agricultural University (Imphal), Manipur

²ICAR-Research Complex for North Eastern Hill Region,

Manipur Centre, Lamphelpat, Imphal West, 795004, Manipur, India

³Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal

*Corresponding Email: shruti.tushi@gmail.com

Abstract

Dragon fruit (*Hylocereus* spp.), a newly introduced superfruit in the Indian market, is surging in popularity among farmers. Its vibrant fruit colors, delectable pulp embedded with edible black seeds, nutraceutical benefits, strong export potential, and high profitability drive this trend. Key insects include ants (*Cardiocondyla* and *Paratrechina* spp.), aphids (*Aphis craccivora*), fruit flies (*Bactrocera* spp.), thrips (*Frankliniella occidentalis*), mealybugs (*Pseudococcus longispinus*), and scale insects (*Diaspis echinocacti*), managed via sanitation, biocontrol (e.g., azadirachtin, predators), and insecticides (e.g., clothianidin, imidacloprid). Major diseases encompass anthracnose (*Colletotrichum* sp.), stem canker (*Neoscytalidium dimidiatum*), stem rot (*Fusarium* sp.), and bacterial soft rot (*Erwinia* and *Enterobacter* spp.), controlled through pruning, disease-free propagules, *Trichoderma*, and fungicides/bactericides (e.g., mancozeb, azoxystrobin, streptomycin). Integrated strategies emphasizing sanitation, biocontrol, and targeted chemicals are vital for sustainable production in tropical climates.

Introduction

Dragon fruit (*Hylocereus polyrhizus*) (Weber) Britton & Rose, a tropical herbaceous perennial climbing cactus bearing edible delicious fruits is native to South America, Central America, and Mexico (Mizrahi *et al.*, 1997). The fruit of the *Hylocereus* species is very nutritious, full of vitamins and minerals, and has several therapeutic and antioxidant qualities. Four species of dragon fruit are grown in several nations. These include *Hylocereus costaricensis* (red skin with purple flesh), *Hylocereus undatus* (red skin with white flesh), *Hylocereus megalanthus* (yellow-skinned fruit with white flesh), and *Hylocereus polyrhizus* (red skin with scarlet flesh). Because of its many bioactive phytochemicals, such as flavonoids, phenols, anthocyanins, and betalains, which support its health-promoting properties, dragon fruit has garnered a lot of attention. Over 2.1 million metric tonnes of dragon fruit are being produced worldwide on 112,000 hectares (2017–18 figures), with Vietnam, China, Indonesia, Thailand, Taiwan, Malaysia, the Philippines, Cambodia, India, and the USA leading the way. China comes in second, producing over 700,000 tonnes from 40,000 hectares, worth US\$397 million, or 33.3% of the global total. The crop was brought to India in the late 1990s (Arivalagan *et al.*, 2019). From 2005 to 2017, India's dragon fruit farming area grew gradually from 4 ha to 400 ha across several states. Initial adoption was spearheaded by pioneering farmers in West Bengal, Andhra Pradesh, Telangana, Andaman & Nicobar Islands, Karnataka, Maharashtra, Gujarat, Kerala, Tamil Nadu, Odisha, and West Bengal. Since then, cultivation has expanded to northeastern states as well as Rajasthan, Punjab, Haryana, Madhya

Pradesh, and Uttar Pradesh. At the moment, Gujarat, Karnataka, and Maharashtra account for over 70% of the country's production (Wakchaure *et al.*, 2021).

Major insect of dragon fruit

1. Ant (*Cardiocondyla* sp. and *Paratrechina* sp.): -

High populations of ants can cause severe damage on the stems, flowers and fruits, when feeding and farming on the plants.

Management:

To eliminate nesting places, orchards should be cleaned up and dried plant remnants removed. Ants have been managed with azadirachtin, which is derived from neem seeds. Ants are managed with a few insecticides, such as clothianidin, thiamethoxam, and abamectin. Ants can be drawn to and killed by applying a mixture of sugar, edible fat, and insecticide to the top of plants.

2. Aphid (*Aphis craccivora*):

Aphids are found on flowers and fruits. The presence of aphids causes green or white spots on the skin of mature fruits.

Management:

Lady beetles and lacewings, as the predators of aphids, are recommended as natural enemies to control aphids. Since aphids are a common pest of many crops, various insecticides such as clothianidin, abamectin, emamectin benzoate, cypermethrin, buprofezin, lambda-cyhalothrin are used to control them.

3. Fruit flies (*Bactrocera* sp.):

Fruit flies lay their eggs by stinging the surface of ripe fruits. Fruits will decay and fall off, and the infected fruit sections will progressively become brown, especially where skin and flesh come into touch.

Management:

To stop fruit flies from spreading throughout orchards, contaminated fruits should be gathered and burnt. Fruits can also be packaged using netting or holed plastic. Fruit flies in dragon fruit plantations can be decreased by using baiting chemicals as attractants or repellents. For instance, male flies are baited with a combination of pesticides (Dacusfly 100SL, Flykil 95EC) and methyl eugenol.

4. Thrips (*Frankliniella occidentalis*):

Typically, thrips are found on fruits and stems that are shaded. The surface of affected regions develops thrips scars as a result. Fruits may have twisted stems with white, glossy patches on the surface and rusty patches on the underside.

Management:

In orchards, weeds should be managed before they bloom, and then insecticides should be applied. Thrips on dragon fruit are biocontrolled with azadirachtin, which is derived from neem seeds. To manage thrips, insecticides such as clothianidin, thiamethoxam, and abamectin are advised.

5. Mealy bugs (*Pseudococcus longispinus*):

Mealybugs on dragon fruit appear as white, cottony masses and cause yellowing, wilting, and drying of shoots, leaves, and fruit.

Management:

Gathering and eliminating all infected plant parts, including leaves, twigs, peduncles, and fruits. raking the soil around the tree area to reveal bug eggs, then repeating the process after a month. Imidacloprid (17.8% SL) foliar sprays at a rate of 0.5 millilitres per litre, spaced 14 days apart. Sulfoxaflor (21.8% w/w SC) at a rate of 0.2 ml per litre should be applied topically no more than twice. 0.5 ml per lit of water at intervals of 14 days for severe infestation.

6. Scale insect (*Diaspis echinocacti*):

Plant stems have been shown to be attacked by the scale insect. It has a stiff scale with a resinous or waxy covering. It causes more harm by producing honeydew and feeding on plant sap. On stems, branches, and occasionally on fruits, scale insects resemble tiny, round, or oval bumps.

Management:

Remove infested stems or branches and prune the plant. Use a soft brush or cloth soaked in isopropyl alcohol to physically remove scale insects from affected area

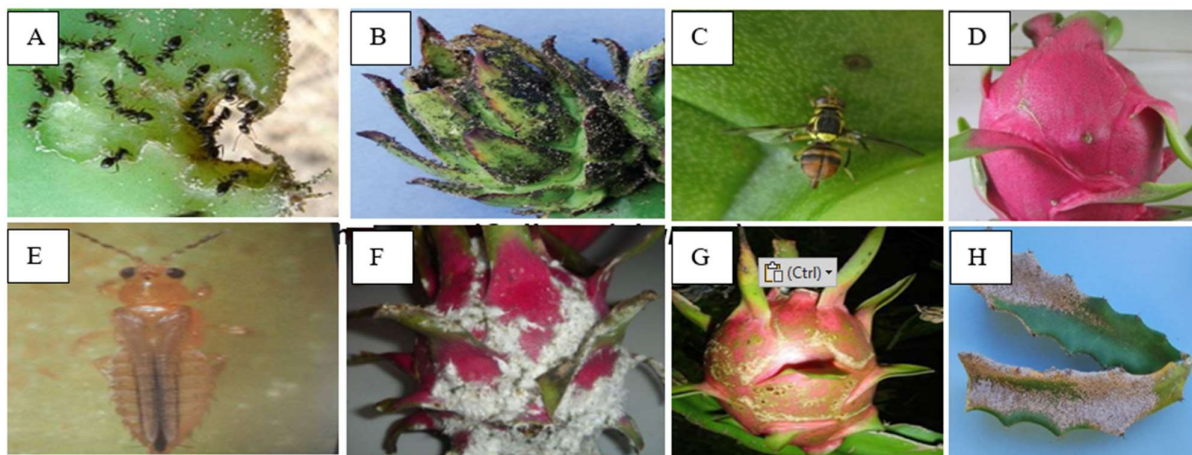
Major Diseases 1. Anthracnose (*Colletotrichum* sp):

Fig.1 (A-H): Insect pest of dragon fruit and their symptoms, (A) Ants, (B) Aphids, (C) Fruit fly, (D) symptoms produce by fruit fly (E) Thrips, (F) Mealy bug, (G-H) Scale insect produce symptoms on both fruit and stem

Anthracnose disease causes damage to flowers, stems and fruits, and reduces crop yields. Anthracnose disease has a characteristic reddish-brown, circular or irregular spots and chlorotic bright yellow halos symptoms on both stems and fruits.

Management:

Removing infected stems and pruning plants after harvesting. Regular applications of Chlorothalonil and Mancozeb are used to control the disease.

2. Stem canker and fruit internal brown rot (*Neoscytalidium dimidiatum*): Symptoms can emerge in young shoots, young fruits and ripe fruits. Initial symptoms are small, circular pale to dark brown sunken lesions or orangish brown/orange lesions. The lesions turn dark brown and form black pycnidia on the surface of the canker.

Management:

Since pathogens transferred from cuttings are the main inoculum in orchards, it is advised to utilise disease-free cuttings for planting. Pruning and removing infected stems and fruits from orchards is the best course of action. Alternatively, they can be broken into small pieces and treated with lime or effective microorganisms (EM) for quick decomposition. *Trichoderma* can be utilised to break down trimmed stems more quickly, which can lower the *N. dimidiatum* inoculum. To control the illness, several fungicides were proposed, including metiram, trifloxystrobin, pyraclostrobin, azoxystrobin, azoxystrobin + difenoconazole, cyprodinil + fludioxonil, and tebuconazole.

3. Stem rot (*Fusarium* sp.):

Symptoms first appear as circular brown sunken lesions, and orange sporodochia and white mycelium form on the lesion surface e.g. *Fusarium equiseti*, *F. longifundum*. (Prakash *et al.*, 2026).

Management: To prevent the inoculum from spreading to healthy stems and plants, infected plant portions should be trimmed. Pitaya fungal infections can be effectively controlled by using disease-free cuttings and maintaining farm sanitation. Stem rot diseases are managed with chemical fungicides including Bordeaux, copper hydroxide, propineb, and thiram.

4. Bacterial soft rot disease (*Erwinia* sp. and *Enterobactor* sp.): A water-soaked blister and tiny bubbles on the skin of young fruit are the first signs. Yellowish to brownish soft, watery lesions that begin to appear on the tips, outside edges of stems, bud bracts, and fruits are typical signs.

Management: For sick dragon fruit plants, excessive water irrigation should be avoided. It has been claimed that applying high organic matter to the soil along with additional antagonist fungus like *Trichoderma* can help. During the rainy season, bactericides such oxolinic acid, streptomycin sulphate, and kasugamycin are applied.

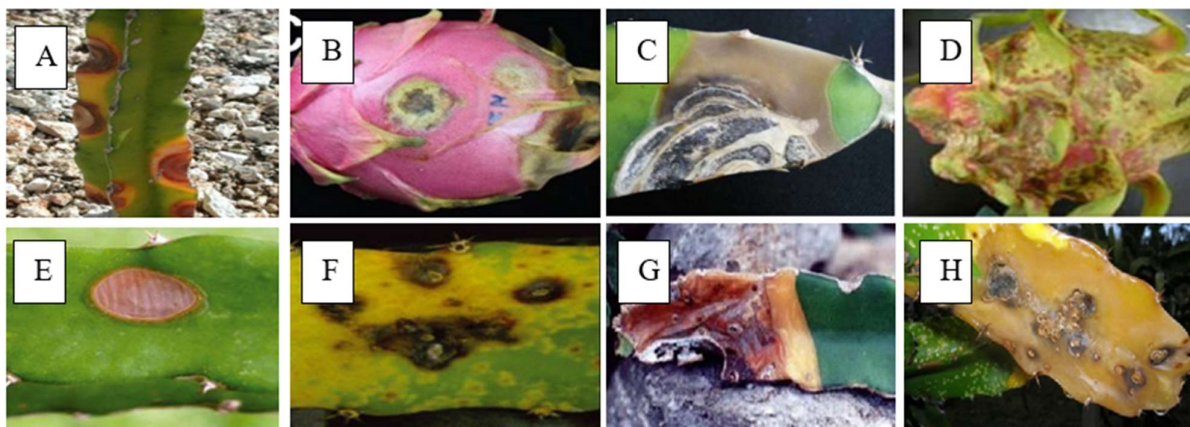


Fig. 2 (A-H) Symptoms of different disease: (A-B) Anthracnose on both stem and fruit, (C-D) Stem canker and fruit internal brown rot, (E-F) Stem rot (*Fusarium* sp.), (G-H) Bacterial soft rot.

Conclusion

Dragon fruit cultivation faces significant challenges from pests and diseases, yet integrated management offers a path to sustainable production. Effective strategies combine sanitation, biological controls like azadirachtin and *Trichoderma* spp., and targeted chemicals such as clothianidin, imidacloprid, mancozeb, and streptomycin to minimize losses. These approaches safeguard yields while preserving the crop's nutritional value, antioxidant properties, and

economic viability in tropical regions like India. Prioritizing disease-free propagules, regular pruning, and vigilant monitoring curbs outbreaks of anthracnose, stem canker, rot, and soft rot, ensuring robust plant health. As global demand rises with production exceeding 2.1 million tonnes annually adopting these practices empowers farmers in states like Gujarat, Karnataka, and Maharashtra to boost profitability and export potential. Ultimately, proactive pest and disease management secures dragon fruit's status as a high-value superfruit, fostering resilient farming systems for long-term food security and market dominance.

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PACKAGING THE FUTURE: SMART, SUSTAINABLE, AND EDIBLE INNOVATIONS IN FOOD SYSTEMS

Nisha Dani ^{1*} and Vishakha Singh²

¹M.Sc. Research Scholar, FSN Department, College of Community & Applied Sciences, MPUAT, Udaipur, Rajasthan, India

²Department of Food Science and Nutrition, College of Community & Applied Sciences, MPUAT, Udaipur, Rajasthan, India

*Corresponding Email: n.nishadani2020@gmail.com

Introduction

The modern food industry has undergone remarkable transformations in response to population growth, urbanization, and changing consumer lifestyles. Among these developments, food packaging has emerged as an indispensable component of food preservation, safety, transportation, and marketing. Packaging protects food products from microbial contamination, oxidation, moisture loss, and physical damage while enhancing shelf stability and consumer convenience. For decades, synthetic petroleum-based plastics have dominated the packaging industry because of their low cost, durability, flexibility, and superior barrier properties. Materials such as polyethylene, polypropylene, and polyethylene terephthalate have become widely used across global food systems.

Despite these advantages, the excessive dependence on plastic packaging has precipitated one of the most serious environmental crises of the twenty-first century. Plastic materials are inherently resistant to biodegradation and may persist in the environment for hundreds of years. According to environmental assessments, millions of tons of plastic waste are generated annually, with food packaging accounting for a substantial proportion of global plastic consumption. Alarmingly, improper disposal practices contribute significantly to soil degradation, marine pollution, ecological imbalance, and greenhouse gas emissions.

The accumulation of microplastics in aquatic ecosystems has further intensified concerns regarding food safety and human health. Scientific studies increasingly suggest that microplastic particles may infiltrate food chains and potable water systems, posing toxicological and physiological risks. Consequently, growing environmental awareness, stricter governmental regulations, and consumer demand for eco-friendly products have accelerated the search for sustainable alternatives to conventional packaging materials.

In this context, smart sustainable edible packaging has emerged as a revolutionary approach capable of simultaneously addressing environmental, technological, and food security concerns. Unlike traditional packaging systems, edible packaging materials are biodegradable and, in many applications, consumable. These advanced packaging technologies are designed not only to preserve food quality but also to reduce packaging waste and environmental burden. The integration of active and intelligent functionalities further enhances their ability to extend shelf life, improve food safety, and maintain product freshness.

The transition beyond conventional plastics toward sustainable edible packaging signifies more than technological innovation; it represents a paradigm shift toward environmentally responsible

food systems, circular bioeconomy practices, and long-term sustainability. Therefore, understanding the mechanisms, benefits, challenges, and future potential of edible packaging technologies has become increasingly important for researchers, policymakers, food industries, and consumers alike.

The Escalating Environmental Burden Of Plastic Packaging

Plastic packaging constitutes one of the largest contributors to environmental pollution worldwide. The widespread utilization of non-biodegradable materials in food systems has resulted in alarming levels of environmental contamination. Synthetic plastics possess exceptional durability and chemical stability; however, these same properties make them highly resistant to microbial decomposition.

Food packaging waste often accumulates in landfills or enters aquatic environments through inadequate waste disposal mechanisms. Marine ecosystems are particularly vulnerable to plastic pollution, as discarded plastics adversely affect biodiversity and threaten aquatic organisms through ingestion, entanglement, and habitat destruction. Moreover, environmental degradation caused by plastics indirectly affects human populations through food chain contamination.

Recent research has highlighted the growing prevalence of microplastics, microscopic fragments generated from plastic degradation. These particles have been detected in seafood, drinking water, table salt, and even atmospheric dust. Scientific evidence increasingly suggests that chronic exposure to microplastics may negatively influence human health through inflammatory responses, endocrine disruption, and toxic chemical accumulation.

Furthermore, plastic manufacturing contributes substantially to carbon emissions due to its dependence on fossil fuels. The production, transportation, and disposal of plastics collectively intensify global climate change concerns. As a result, governments worldwide have introduced policies aimed at reducing single-use plastics and encouraging biodegradable packaging innovations.

A New Era Of Sustainable Food Packaging

Smart sustainable edible packaging refers to innovative packaging systems developed from biodegradable and renewable biological materials capable of protecting food products while minimizing environmental impact. Unlike conventional packaging, edible materials may either naturally degrade after disposal or be safely consumed alongside food products.

These packaging systems are typically manufactured using naturally derived compounds such as proteins, polysaccharides, lipids, and plant-based fibers. Such biomaterials possess the ability to form thin edible films and coatings that function as semipermeable barriers against environmental factors responsible for food spoilage.

The defining feature of smart packaging lies in its multifunctionality. Traditional packaging merely acts as a passive barrier, whereas smart edible packaging actively interacts with food products and surrounding environments to preserve quality and freshness.

For example, intelligent edible films may incorporate:

- Antimicrobial compounds to inhibit microbial growth and foodborne pathogens
- Natural antioxidants to delay oxidation and maintain nutritional quality
- Freshness indicators that detect spoilage-related chemical changes

- Moisture and oxygen regulators that maintain food stability during storage

These integrated functionalities significantly improve food safety, nutritional preservation, and shelf-life extension.

Types Of Sustainable Edible Packaging Systems

1. **Edible Films:** Thin biodegradable layers used as food wraps or directly applied to food. They protect against moisture, oxygen, and microbial contamination, helping maintain freshness and quality.
2. **Edible Coatings:** Protective layers applied directly to food surfaces to reduce moisture loss, oxidation, and spoilage while extending shelf life.
3. **Active Packaging Systems:** Packaging containing functional compounds such as antioxidants or antimicrobials that actively preserve food quality and delay spoilage.
4. **Intelligent or Smart Packaging:** Advanced packaging that monitors food freshness using indicators or sensors to detect spoilage and improve food safety.

Major Advantages Of Smart Sustainable Edible Packaging

1. **Environmental Sustainability:** Reduces plastic waste through biodegradable materials and supports eco-friendly resource utilization.
2. **Improved Shelf Life:** Protects food from moisture, oxygen, microbes, and oxidation, thereby preserving freshness and quality.
3. **Reduction in Food Waste:** Enhances food preservation, minimizing spoilage during storage and transportation.
4. **Enhanced Consumer Safety:** Improves food safety through antimicrobial protection and reduced chemical contamination.
5. **Economic Opportunities:** Creates market potential for sustainable products, promoting industrial innovation and green entrepreneurship.

Key Challenges In Smart Sustainable Edible Packaging

1. **Limited Strength and Durability:** Edible packaging often has lower mechanical strength and moisture resistance compared to conventional plastics, limiting its application.
2. **High Manufacturing Cost:** Production requires advanced technologies and specialized materials, increasing overall costs.
3. **Consumer Awareness and Acceptance:** Concerns about hygiene, taste, texture, and lack of familiarity may influence consumer preference.
4. **Safety and Regulatory Issues:** Strict food safety regulations and quality standards are necessary for commercialization and consumer protection.

Recent Innovations In Sustainable Edible Packaging

1. **AI-Based Smart Packaging:** Artificial intelligence and smart sensors help monitor food freshness, detect spoilage, and optimize storage conditions.
2. **Nanotechnology Applications:** Nanomaterials improve strength, antimicrobial activity, and barrier properties of edible packaging.
3. **Bioactive Packaging Systems:** Natural antioxidants and antimicrobial compounds enhance shelf life and preserve food quality.
4. **Circular Bioeconomy Approach:** Agricultural and food waste can be transformed into biodegradable packaging materials, supporting sustainability.

Contribution To Sustainable Development Goals (Sdgs)

1. **Consumption (SDG 12):** Reduces packaging waste.
2. **Climate Action (SDG 13):** Lowers plastic pollution and carbon footprint.
3. **Life Below Water (SDG 14):** Minimizes marine plastic contamination.
4. **Life on Land (SDG 15):** Protects biodiversity and ecosystems.

Transforming The Future of Food Packaging

The future of sustainable edible packaging is highly promising due to increasing environmental concerns, technological advancements, and growing consumer demand for eco-friendly alternatives. Future developments may include freshness indicators, biodegradable smart sensors, antimicrobial coatings, and intelligent preservation systems that can monitor food quality, detect spoilage, and enhance food safety in real time.

Advancements in nanotechnology and biomaterials are expected to improve the mechanical strength, moisture resistance, flexibility, and shelf stability of edible packaging materials, making them more effective substitutes for conventional plastics. Additionally, the incorporation of natural antioxidants and antimicrobial compounds may further extend shelf life and reduce microbial contamination.

Artificial intelligence and smart packaging technologies may also play a crucial role in optimizing storage conditions, tracking product freshness, and reducing food wastage across supply chains. Furthermore, increasing government regulations on plastic use and rising awareness regarding environmental sustainability are likely to accelerate industrial adoption and commercialization.

In the coming years, sustainable edible packaging has the potential to revolutionize the food packaging industry by offering safer, biodegradable, and environmentally responsible solutions that support sustainable food systems and global environmental protection.

Conclusion

Smart sustainable edible packaging represents a promising and environmentally responsible alternative to conventional plastic packaging in the food industry. By improving food preservation, extending shelf life, reducing microbial contamination, and minimizing food waste, it contributes significantly to the development of sustainable food systems. Unlike traditional petroleum-based plastics, edible and biodegradable packaging materials help reduce environmental pollution, landfill burden, and plastic accumulation in terrestrial and aquatic ecosystems.

In addition to its environmental advantages, smart edible packaging integrates innovative features such as antimicrobial activity, antioxidant protection, and freshness-monitoring systems that enhance food quality and safety. These advanced technologies not only support consumer health but also improve storage efficiency and reduce post-harvest losses.

Despite challenges related to production cost, mechanical strength, storage stability, regulatory approval, and consumer acceptance, ongoing advancements in food science, biomaterials, nanotechnology, and artificial intelligence are continuously improving the effectiveness and commercial viability of sustainable packaging systems. Furthermore, increasing environmental awareness, government regulations on single-use plastics, and rising consumer demand for ecofriendly products are expected to accelerate their adoption globally.

Therefore, the transition from conventional plastics to smart sustainable edible packaging is not merely an innovation but an essential step toward achieving environmental sustainability, responsible consumption, and a cleaner, healthier future for coming generations.

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INTEGRATING ECOSYSTEM SERVICES AND ENVIRONMENTAL ECONOMICS: COMPUTATIONAL TOOLS AND AUDITING FRAMEWORKS FOR SUSTAINABLE PLANNING

Harsh Pandey^{1*}, Padmanabha A¹ and Kusumlata Goswami¹

College of Fisheries Science,
Chaudhary Charan Singh Haryana Agricultural University (CCSHAU),
Hisar-125004, Haryana

*Corresponding Email: harshpandey99777@gmail.com

Introduction: Reimagining Our Capital

For generations, classical economic models operated on a flawed assumption: that nature is an infinite, self-replenishing backdrop to human industry. Forests were valued only when timbered; rivers were quantified by the gallons diverted for factories or agricultural irrigation.

Today, rapid climate shifts, resource scarcity, and ecosystem collapses have forced a profound paradigm shift. We now recognize that the global economy is entirely nested within Earth's biosphere. Merging ecology, economic theory, and computational analytics into regional planning is no longer a niche academic exercise; it is an absolute necessity for long-term survival.

Ecosystem Services: Nature's Silent Balance Sheet

Ecosystem services are the direct and indirect contributions that ecosystems provide to human survival and quality of life. Rather than treating these benefits as amorphous concepts, the global scientific community categorizes them into four distinct functional domains:

Provisioning Services: Tangible material outputs harvested directly from nature, such as clean drinking water, timber, wild fish stocks, medicinal plants, and food crops.

Regulating Services: The systemic stabilizing functions of natural processes. For example, wetlands and floodplains act as natural sponges during heavy downpours to prevent urban flooding, while mangrove forests serve as physical barriers against coastal storm surges.

Supporting Services: Fundamental ecological processes that underpin all other services. These include soil formation, nutrient cycling (carbon, nitrogen, and phosphorus), and primary biomass production. Without these, the biosphere ceases to function.

Cultural Services: The non-material benefits that enrich human society, including recreational spaces, aesthetic inspiration, spiritual connection to landscapes, and eco-tourism opportunities.

When these services break down, human infrastructure must step in at an astronomical financial cost. Artificial water filtration plants must replace degraded upstream watersheds, and engineered concrete sea walls must take the place of destroyed coastal ecosystems.

Environmental Economics: Pricing the Priceless

How do we prevent a wetland from being paved over for a strip mall when its market value as real estate is obvious, but its value as a natural flood defense is invisible on a balance sheet? This is the core dilemma of environmental economics.

Because ecosystem services lack traditional market prices, they are routinely treated as "free goods," leading to overexploitation—a classic economic failure known as the Tragedy of the

Commons. To fix this market failure, economists utilize a framework called Total Economic Value (TEV) (Gómez-Baggethun *et al.*, 2010).

Use Values

Direct Use Value: Consumptive or non-consumptive utilization of resources (e.g., catching fish or hiking in a park).

Indirect Use Value: Functional benefits provided by nature that protect or support economic activity (e.g., carbon storage by global forests or pollination of commercial orchards by wild insects).

Option Value: The premium paid to preserve an environmental asset for potential future use, such as protecting an unexplored rainforest for its potential to yield life-saving pharmaceutical compounds.

Non-Use Values

Existence Value: The value derived simply from knowing an ecosystem or species exists, independent of any human intention to use it (e.g., protecting blue whales from extinction).

Bequest Value: The value placed on preserving natural resources and pristine environments for future generations to experience.

Historically, groundbreaking work sought to put a dollar figure on these services to illustrate their magnitude, finding that global ecosystem services routinely dwarf global Gross National Product (Costanza *et al.*, 1997). Over time, as landscapes degrade due to land-use changes, the net loss of these services costs the global economy trillions of dollars annually (Costanza *et al.*, 2014).

Analysis and Computation: Modelling the Complexity

Translating the qualitative realities of ecology into the quantitative frameworks required by policymakers demands advanced analytical and computational tools. Because ecosystems are highly dynamic, spatial, and interconnected, simple static spreadsheets are entirely inadequate.

Modern environmental planning relies heavily on integrated software platforms. Spatially explicit modeling tools, such as InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) and ARIES (Artificial Intelligence for Environment and Sustainability), couple spatial data from Geographic Information Systems (GIS) and remote sensing with predictive economic models. These frameworks allow researchers to map out exactly how service delivery changes under different landscape management scenarios (de Groot *et al.*, 2012).

Methodologies of Valuation

To fuel these computational systems, environmental economists deploy specific quantitative estimation techniques:

Market-Based Methods: Used when an ecosystem service directly impacts a priced market. This includes the Production Function Approach (calculating how a drop in water quality directly reduces downstream agricultural yields) and Replacement Cost Methods (estimating how much it would cost to build an engineering equivalent if a natural service were lost).

Revealed Preference Methods: Inferring economic value based on observed human behavior in related markets. The Travel Cost Method calculates the economic value of a national park based on what visitors spend on fuel, travel time, and entry fees to get there. The Hedonic Pricing

Method isolates the environmental component of property values, demonstrating how proximity to clean water or green spaces premiums real estate prices.

Stated Preference Methods: Deploying highly structured surveys to capture non-use values where no market proxy exists. Contingent Valuation directly asks individuals their maximum "Willingness to Pay" (WTP) to preserve a specific habitat or endangered species.

Environmental Auditing: Driving Accountability

If economic valuation gives us a map of natural capital, environmental auditing provides the mandatory report card tracking our compliance. An environmental audit is a systematic, documented, and objective evaluation of an organization's operational activities against explicit environmental benchmarks. (fig.1.)



"Framework for Assessing Ecosystem Services and Their Application in Environmental Economics, Auditing, and Policy Planning."

Strategic Importance in Planning and Sustainable Development

Integrating these elements—ecosystem service mapping, economic valuation, computational modeling, and environmental auditing—completely transforms land-use planning and regional development.

Historically, municipal planning treated environmental protection as a restrictive regulatory hurdle that slowed economic growth. When built upon a foundation of environmental economics, planning becomes an optimization problem designed to maximize long-term systemic wealth.

When urban developers or regional planners design infrastructure with these tools, they can clearly run trade-off analyses (Woodruff & BenDor, 2016). Rather than focusing solely on agricultural expansion or real estate development, spatial planning can proactively target alternative development paths that conserve critical wild-species diversity while maximizing net environmental benefit (Bateman *et al.*, 2013). This structural decision-making process helps make public resource allocation defensible, efficient, and transparent (Martinez-Harms *et al.*, 2015).

Computational analysis can prove that the wetland's natural capacity for flood mitigation, wastewater filtration, local fisheries support, and carbon sequestration provides a higher net

present value to the community than the short-term financial gains of industrial development. This systemic integration shifts development from an exploitative trajectory to a genuinely sustainable one, equipping governments with the precise metrics needed to preserve our shared ecological heritage.

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CLIMATE-RESILIENT CROPS: INDIA'S ECONOMIC SHIELD AGAINST A FUTURE SUPER EL NINO

Manoj Kumar Dara^{1*}, Praveen Kumar Verma¹ and M. J. S. L. Naga Durga²

¹PhD. Scholar, Department of Agricultural Economics, IGKV, Raipur – 492012 (C.G).

²Assistant Professor, Department of Agricultural Economics, IGKV, Raipur – 492012 (C.G).

*Corresponding Email: manojkumardara.agecon@gmail.com

Abstract

Climate variability, particularly the increasing likelihood of future Super El Niño events, poses a significant threat to Indian agriculture, food security, and economic stability. This paper examines the economic implications of El Niño-induced climatic shocks and highlights the role of climate-resilient crops as a strategic adaptation measure. Drawing upon recent scientific evidence and policy literature, the study discusses the resilience potential of millets, pulses, and climate-tolerant horticultural crops in reducing production risks, stabilizing farm incomes, and moderating food inflation. The paper argues that promoting climate-resilient agriculture through crop diversification, improved seed systems, water-smart technologies, climate information services, crop insurance, and Farmer Producer Organizations can strengthen India's agricultural resilience and serve as an effective economic shield against future climate-induced uncertainties.

Keywords: Climate-resilient crops, Super El Niño, Agricultural resilience, Food security.

Introduction

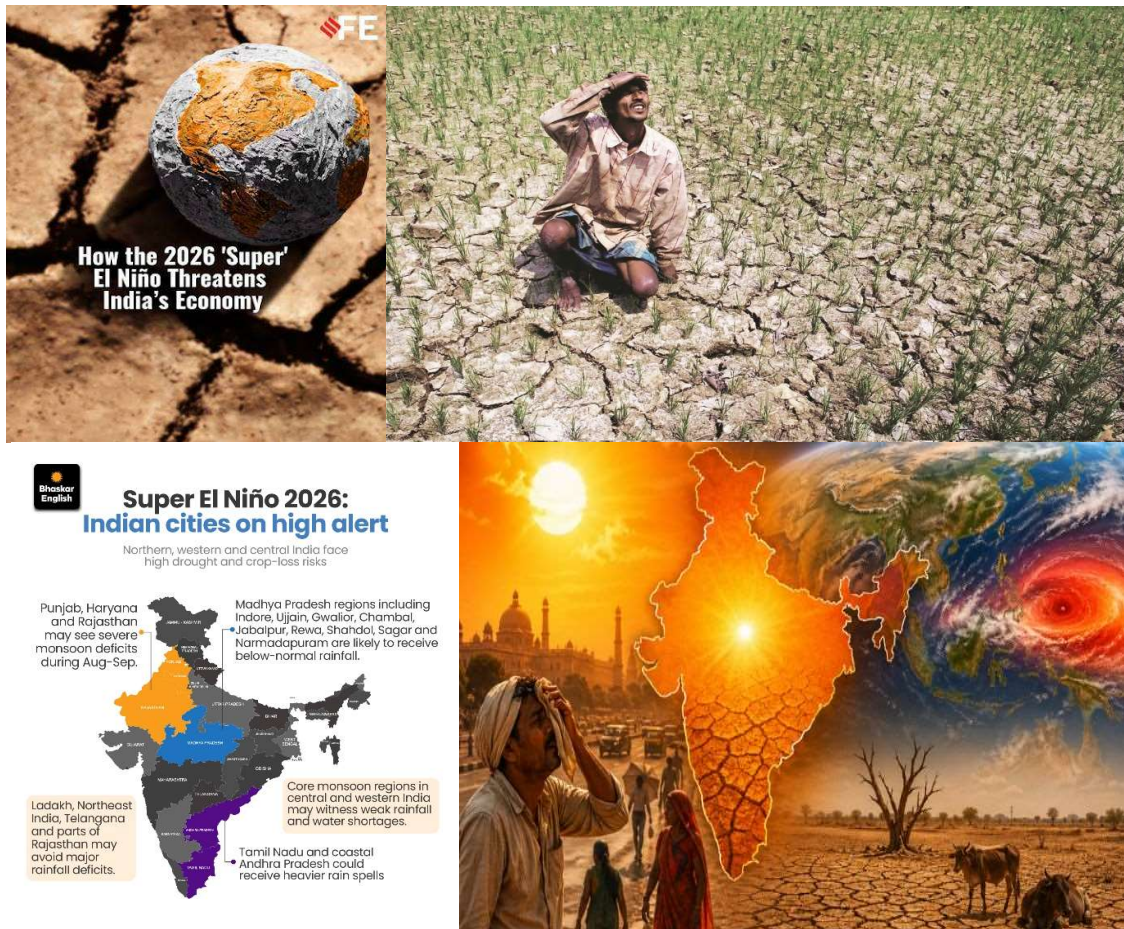
Indian agriculture is entering an era of unprecedented climatic uncertainty. Rising temperatures, erratic rainfall patterns, increasing frequency of droughts and floods, and recurring extreme weather events are fundamentally altering agricultural production systems. Among the climatic phenomena affecting India, the El Niño Southern Oscillation (ENSO) remains one of the most influential drivers of monsoon variability and agricultural performance. Agriculture continues to play a crucial role in the Indian economy, contributing approximately 17–18 percent of Gross Value Added (GVA) while supporting the livelihoods of nearly half of the country's population. However, nearly 52 percent of India's net sown area remains rainfed and heavily dependent on monsoon rainfall, making agricultural production highly vulnerable to climatic fluctuations. The possibility of future Super El Niño events raises serious concerns not only for agricultural production but also for farm incomes, food security, rural employment, inflation management, and overall economic stability. In this context, climate-resilient crops are increasingly being recognized as a strategic solution for enhancing agricultural sustainability and economic resilience.

Understanding the Economic Significance of Super El Niño

El Niño refers to the abnormal warming of sea surface temperatures in the central and eastern tropical Pacific Ocean, which weakens atmospheric circulation patterns and often reduces monsoon rainfall over India. While El Niño is commonly viewed as a meteorological phenomenon, its real significance lies in its economic consequences. The global impacts of El Niño are enormous. The 1997–98 El Niño caused approximately 23,000 disaster-related deaths worldwide and generated economic losses estimated at US\$45 billion. Similarly, the 2015–16 El Niño affected nearly 60 million people globally through droughts, floods, food shortages, and livelihood disruptions. For India, the consequences of El Niño are particularly severe because agriculture

remains highly dependent on monsoon rainfall. Reduced rainfall directly affects crop production, livestock productivity, groundwater recharge, reservoir storage, and rural incomes. The economic transmission mechanism is straightforward:

El Niño → Weak Monsoon → Reduced Crop Production → Lower Farm Income → Food Inflation → Reduced Rural Demand → Economic Slowdown



Thus, El Niño should be viewed as an economy-wide shock rather than merely an agricultural event.

Evidence of El Niño Impacts on Indian Agriculture

Scientific evidence consistently demonstrates the influence of ENSO on agricultural production. Bhatla et al. (2020) analyzed the impact of El Niño and La Niña events across different agro-climatic zones of the Indo-Gangetic Plains and found significant effects on rice, maize, pulse, and sugarcane production. Rice production was particularly vulnerable in the middle and upper Indo-Gangetic regions during El Niño years. Pulse production also declined substantially across multiple regions. Similarly, a micro-level study conducted in Karnataka observed that southwest monsoon rainfall remained below normal across most districts during El Niño years. The study demonstrated a strong relationship between ENSO-induced rainfall variability and rice production, highlighting the importance of climate forecasting for agricultural planning. These findings confirm that climatic variability directly influences foodgrain production and agricultural incomes.

Climate-Resilient Crops as Risk-Reducing Assets

Traditional agricultural policy focused on maximizing productivity. However, climate change requires a transition toward resilience-oriented agriculture. Climate-resilient crops are capable of maintaining productivity under drought, heat stress, floods, salinity, and pest pressure. These crops reduce yield variability and improve income stability. From an economist's perspective, climate-resilient crops function as **risk-reducing assets**. Instead of maximizing output during favorable years, these crops minimize losses during unfavorable years. A crop that yields slightly less during normal years but survives droughts may generate higher long-term economic returns than a high-yielding but climate-sensitive crop.

Millets: The Future of Climate-Resilient Agriculture

Millets have emerged as India's most promising climate-resilient crops. Important millets include: Pearl Millet (Bajra), Sorghum (Jowar), Finger Millet (Ragi), Kodo Millet, Little Millet.

Millets require significantly less water than rice, tolerate drought and heat stress, and perform well under marginal conditions. Economically, millets provide several advantages: Lower production costs, Reduced irrigation requirements, Greater resilience during droughts, Stable yields under climatic stress, Improved nutritional outcomes.

These characteristics make millets particularly valuable for rainfed regions such as Chhattisgarh, Odisha, Madhya Pradesh, Maharashtra, and Rajasthan.

Pulses: Combining Resilience with Nutrition

Pulses constitute another important category of climate-resilient crops. Major pulse crops include: Pigeon Pea (Tur), Green Gram (Moong), Black Gram (Urad), Chickpea (Gram). Pulses offer multiple benefits: Lower water requirements, Nitrogen fixation, Reduced fertilizer dependency, Enhanced soil fertility, Stable market demand. For smallholders, pulses serve both economic and ecological functions, contributing to income diversification and soil health improvement.

Climate-Resilient Vegetables and Nutritional Security

Climate resilience is equally important in horticulture. India's vegetable sector occupies approximately 11.35 million hectares and produces over 204.83 million tonnes annually. The sector contributes nearly ₹7 lakh crore to the economy and accounts for approximately 2.5 percent of national GDP. Research from ICAR-Indian Institute of Vegetable Research highlights the importance of underutilized vegetables, indigenous leafy vegetables, tree vegetables, and climate-resilient horticultural systems in strengthening food and nutritional security under changing climatic conditions. Diversification into resilient vegetable systems can generate employment, improve incomes, and strengthen dietary diversity.

Climate-Resilient Agriculture and Food Inflation

One of the least appreciated consequences of El Niño is food inflation. Agricultural production shocks often result in: Reduced market arrivals, Supply shortages, Rising food prices, Increased inflation. Since food expenditure constitutes a significant portion of household budgets, especially among low-income households, food inflation disproportionately affects vulnerable populations. Climate-resilient crops help moderate inflation by stabilizing food supplies during adverse weather conditions. Consequently, promoting climate-resilient agriculture should be viewed not only as an agricultural policy but also as an inflation-management strategy.

Diversification: The Portfolio Approach to Farming

Agricultural economists frequently compare farming decisions to investment portfolios. Just as investors diversify assets to reduce risk, farmers can diversify crops to reduce production uncertainty. Examples include: Kodo Millet + Pigeon Pea, Little Millet + Green Gram, Sesame + Pigeon Pea, Sorghum + Black Gram. These diversified systems reduce dependence on a single crop and enhance resilience against climatic shocks. The probability of simultaneous failure across all enterprises is significantly lower than in monocropping systems.

Policy Priorities for Climate Resilience

India's future agricultural strategy should prioritize expanding millet procurement, strengthening climate-resilient seed systems, improving climate information services, promoting water-smart agriculture, enhancing crop insurance coverage, and empowering Farmer Producer Organizations (FPOs). Together, these interventions can improve resilience, enhance farmers' incomes, and support sustainable agricultural development in the face of growing climate uncertainty.

Conclusion

The challenge posed by future Super El Niño events extends far beyond rainfall deficits and crop losses. Climate-resilient crops such as millets, pulses, oilseeds, climate-tolerant vegetables, and improved crop varieties offer a practical pathway toward reducing climate risks while stabilizing farm incomes and food supplies. From an economic perspective, these crops generate a triple dividend: reduced production risk, improved income stability, and lower food-price volatility. In an era of climate change and recurring Super El Niño events, the goal must shift toward maximizing resilience under unfavorable conditions. Investments in climate-resilient agriculture should therefore be viewed not as environmental expenditures but as strategic economic investments in India's food security, inflation management, and sustainable rural development.

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CARBON FARMING: A PATH TO CLIMATE MITIGATION AND ENHANCED CARBON CREDITS

**M. A. Sojitra^{1*}, P. M. Kyada², D. B. Balas¹, N. K. Pampaniya¹,
P.A. Damor¹ and A. N. Kunapara¹**

¹College of Agricultural Engineering and Technology, Anand Agricultural University,
Godhra, Gujarat

²Farm Science Centre, Likbharati, Sanosara, Bhavanagar, Gujarat

*Corresponding Email: manojsojitra@aau.in

Abstract

Carbon farming is an innovative approach to combating climate change that uses agricultural practices to sequester carbon dioxide in soils and vegetation. This article explores its techniques, benefits, and challenges, and examines how it enhances carbon credits — covering practice selection, quantification of sequestration, verification, market engagement, and long-term maintenance. Through case studies, it illustrates carbon farming's potential to mitigate climate change while benefiting ecosystems and livelihoods.

Introduction

Carbon farming has emerged as a promising approach in the fight against climate change, offering a practical way to draw down atmospheric carbon dioxide through everyday agricultural and land management practices (Debernardini *et al.*, 2025). Rather than simply cutting emissions at the source, carbon farming works primarily through sequestration — capturing CO₂ from the atmosphere and locking it into soils, vegetation, and organic matter. Some practices also reduce on-farm emissions directly, but sequestration is the core mechanism (Singh *et al.*, 2024).

Beyond its climate benefits, carbon farming creates a financial incentive: sequestered carbon can be converted into carbon credits, tradable certificates that typically represent one metric ton of CO₂ (or its equivalent) removed, reduced, or avoided. This gives farmers and landowners a market-based reason to adopt sustainable practices, turning environmental stewardship into a revenue stream (Raina *et al.*, 2024).

Understanding Carbon Farming

Carbon farming covers a range of techniques designed to sequester carbon while improving soil health. Common practices include:

- **Afforestation and reforestation** — planting trees on degraded or deforested land to create new forests or restore existing ones (Zomer *et al.*, 2008)
- **Conservation tillage** — minimizing soil disturbance during planting and cultivation to reduce carbon loss from soil (Busari *et al.*, 2015)
- **Cover cropping** — planting cover crops during fallow periods to protect soil and increase organic matter (Yan *et al.*, 2025)
- **Rotational grazing** — managing livestock movement to promote grassland carbon sequestration and soil health (Simmons *et al.*, 2026)
- **Agroforestry** — integrating trees with agricultural crops or livestock systems to enhance carbon sequestration and biodiversity (Sharma *et al.*, 2025)

- **Compost and biochar application** — adding organic amendments to soil to increase carbon storage and improve fertility (Nobile *et al.*, 2022)

Adopting sustainable practices alongside these techniques — reducing synthetic fertilizer and pesticide use, promoting crop rotation and diversity, improving water management, and strengthening agroecosystem functions — further supports carbon sequestration, soil health, and resilience.

Enhancing Carbon Credits

Carbon farming enhances the generation of carbon credits by quantifying and monetizing the carbon sequestered through agricultural practices. This requires rigorous measurement, reporting, and verification (MRV) of carbon stocks to ensure the credibility and integrity of the credits produced (Vanderheyden *et al.*, 2026). The process generally involves:

1. **Quantifying carbon sequestration.** Estimating changes in soil carbon stocks, aboveground biomass, and vegetation cover over time, typically using established scientific methodologies or carbon accounting software.
2. **Verification and certification.** Seeking independent verification through recognized schemes such as the Verified Carbon Standard (VCS) or the Climate Action Reserve (CAR), which set rigorous standards for validating carbon offset projects.
3. **Registering carbon credits.** Registering projects with carbon credit registries or trading platforms. Each credit typically represents one metric ton of CO₂ equivalent (CO₂e) sequestered or avoided, and can be sold in voluntary or compliance markets.
4. **Market engagement.** Selling credits through carbon offset auctions, purchase agreements, or partnerships with offset retailers and brokers.
5. **Long-term monitoring and maintenance.** Continuously tracking and maintaining projects to ensure ongoing sequestration and environmental co-benefits, since credibility depends on sustained performance over the project's lifetime.

Key Benefits of Carbon Farming

1. **Climate change mitigation.** Carbon farming sequesters carbon dioxide from the atmosphere, reducing greenhouse gas concentrations and helping mitigate global warming.
2. **Soil health improvement.** Many carbon farming practices increase organic matter content, improve water retention, and enhance nutrient cycling — supporting both sequestration and resilient agricultural production.
3. **Biodiversity conservation.** Agroforestry, reforestation, and related techniques create habitat corridors, promote native species diversity, and restore degraded ecosystems, strengthening resilience and ecosystem services such as pollination and water purification.
4. **Economic opportunities for farmers.** Carbon credits give farmers and landowners a way to diversify income, access new markets, and improve the long-term viability of their operations.

Challenges and Considerations

- **Technical and financial barriers.** Implementing carbon farming requires expertise, investment, and access to land, seeds, and equipment. Supportive policy, incentives, and capacity-building are especially important for smallholder farmers and rural communities.
- **Measurement and verification.** Accurately quantifying sequestration is difficult given variability in soil types, climate, and management practices. Standardized methodologies

and independent verification are essential to maintaining credit integrity — and there remains an ongoing risk of "reversal," where carbon is re-released if land use changes or practices aren't sustained.

- **Socioeconomic impacts.** Projects should account for land tenure rights, labor dynamics, and resource access, using participatory approaches and equitable benefit-sharing to ensure social acceptability.
- **Market dynamics.** Viable, transparent carbon markets are essential. Issues such as additionality (would the sequestration have happened anyway?) and leakage (does the practice simply shift emissions elsewhere?) must be addressed to sustain investor confidence.
- **Policy and institutional support.** Governments, international bodies, and civil society need to build supportive policy and regulatory frameworks, with coordinated action across national, regional, and global levels to mainstream carbon farming into climate strategy.

Case Studies and Success Stories

- **The Australian Carbon Farming Initiative** enables farmers and land managers to earn carbon credits through eligible practices such as reforestation, revegetation, and soil carbon sequestration (Baumber *et al.*, 2019).
- **The Regenerative Agriculture Program (Costa Rica)** incentivizes smallholder farmers to adopt agroecological practices that improve soil health, biodiversity, and carbon sequestration while strengthening livelihoods (Anonymous, 2025).
- **The Africa Soil Carbon Sequestration Program** promotes sustainable land management across sub-Saharan Africa to increase soil carbon stocks, improve food security, and mitigate climate impacts (Vågen *et al.*, 2005).
- **The Agroforestry Carbon Sequestration Project (India)** supports rural communities in establishing agroforestry systems that sequester carbon, conserve biodiversity, and generate carbon credits for voluntary and compliance markets (Gopinath *et al.*, 2025).

Conclusion

Carbon farming offers a promising pathway to enhance carbon credits and address climate change by harnessing the potential of agriculture and land management to sequester carbon. By incentivizing sustainable practices, empowering farmers, and fostering collaboration between stakeholders, it can contribute to a more resilient, equitable, and sustainable future. Realizing its full potential, however, requires concerted effort to overcome technical, financial, policy, and institutional challenges — and to ensure the benefits are shared equitably among communities and ecosystems. Through innovation, collaboration, and sustained action, carbon farming can play a vital role in shaping a low-carbon, climate-resilient economy for future generations.

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ORGANIC SEED PRODUCTION AND CERTIFICATION: A STEP TOWARDS SUSTAINABLE FARMING IN INDIA

**Ashish Sheera^{*1}, Kailash Chandra¹, Vijay Kamal Meena²,
Varsha Kumari¹ and Manoj Kumar Meena¹**

¹S. K. N. Agriculture University, Jobner, Rajasthan 303329, India

²Agriculture University Jodhpur, Rajasthan, 342304, India

*Corresponding Email: sheeraashish@gmail.com

Abstract

Organic seeds serve as the foundation of sustainable agriculture, ensuring ecological balance, crop resilience, and food security. Although India leads globally in the number of organic farmers and holds a vast agricultural area under organic cultivation, its organic seed sector is still in its infancy. This paper explores the core principles and management practices involved in organic seed production, alongside India's primary certification systems NPOP and PGS-India. While initiatives like PKVY and seed hubs offer valuable support, the industry faces real hurdles, including steep certification costs, a shortage of dedicated seed zones, and strong competition from commercial hybrids. To build a self-reliant system, there is a clear need to strengthen community-based seed banks, simplify certification, and focus on region-specific organic plant breeding. Addressing these gaps will be crucial for achieving true seed sovereignty and sustaining the organic movement.

Keywords: Organic Seeds, Organic Farming, Seed Production, Certification

Introduction

Organic agriculture is gaining momentum as a sustainable and environmentally responsible farming system. At the core of this system lies the organic seed—an input that not only initiates the production cycle but also determines the crop's performance, resilience, and ecological compatibility (Gomiero, 2018). Organic farming is not merely the absence of synthetic inputs but the nurturing of a balanced agroecosystem. The seed, being the fundamental unit of agriculture, must be aligned with the principles of organic farming (IFOAM, 2005). If the seed is not organically produced, the integrity of the entire organic system is compromised.

Organic farming contributes significantly to ecological sustainability. Research shows that ecological production fields support approximately 30% more wildlife and plant diversity than conventional fields, largely due to the absence of chemical pesticides and minimal use of synthetic fertilizers. Organic farms are often teeming with birds, insects, and animals, serving as vibrant hubs of biodiversity.

The COVID-19 pandemic further shifted consumer perception towards safer and more nutritious food, bringing attention to the concept of nutritional security rather than just food security focused on caloric intake. Organically grown food is now increasingly viewed as a preferred choice due to its higher antioxidant levels, absence of harmful residues, and support for environmental health and sustainability.

India accounts for the highest number of organic producers globally, comprising approximately 36% of the world's total, and ranks second in total organic agricultural area with around 4.74 million hectares under cultivation (FiBL & IFOAM, 2025). With 4.5 million organic farmers and a

steadily expanding sector, the country continues to lead in sustainable farming efforts. Despite this progress, organic seed production and certification remain in a nascent stage, requiring targeted attention, innovation, and policy support to ensure the integrity and sustainability of India's organic agriculture (Chandra et al., 2021).

What are Organic Seeds

Organic seeds are produced using methods that avoid synthetic fertilizers, pesticides, genetically modified organisms (GMOs), and chemical treatments. They are developed under conditions that promote soil health, ecological balance, and pest resistance (Merfield, 2012).

Importance of Organic Seeds

- **Adaptability:** Optimized for nutrient cycling, pest resistance, and climate adaptability (Nuijten et al., 2017)
- **Biodiversity:** Encourages the use of landraces and local varieties (Micheloni & Giubilato, 2004)
- **Certification Compliance:** Mandatory for organic exports under NPOP and PGS (APEDA, 2020a)
- **Seed Sovereignty:** Empowers farmers and supports community seed banks (Walz, 2004)

What is Organic Seed Production

Organic seed production refers to cultivating seeds under certified organic conditions, ensuring genetic and physical purity, ecological adaptability, and compliance with National Organic Standards (NOS) (APEDA, 2020b). A conversion period of at least two to three years is required, depending on crop type, for certification (APEDA, 2020b; Chandra et al., 2021).

Key Steps in Organic Seed Production

- **Field Selection**
 - Land must undergo 2–3 years of organic management
 - Maintain buffer zones and isolation distance
- **Variety Selection**
 - Use open-pollinated or indigenous varieties
 - Avoid genetically engineered materials
- **Crop Management**
 - Use botanical extracts (e.g., neem), green manure, and biofertilizers
- **Harvesting and Storage**
 - Harvest at physiological maturity
 - Use natural preservatives like neem leaves or ash

Certification of Organic Seeds in India

1. NPOP (National Programme for Organic Production)

- Administered by APEDA, Ministry of Commerce
- Globally recognized (EU & USA)
- Certification by accredited agencies like ECOCERT, INDOCERT, RSOCA
- Use of organic seeds is mandatory; non-GMO untreated seeds allowed only under derogation (APEDA, 2020a)

2. PGS-India (Participatory Guarantee System)

- Managed by NCOF under Ministry of Agriculture
- Cost-effective, decentralized model for smallholders

- Promotes local seed use and flexible transitional arrangements (APEDA, 2020b)

Certification Process Includes:

- Field inspections and verification of conversion period
- Buffer zone enforcement and GMO testing
- Labelling, tagging, and documentation checks (Chandra et al., 2021)

Organic Certification Mark: "India Organic"

This is the official India Organic logo used under the National Programme for Organic Production (NPOP):



- The blue arc represents cosmic force or universal purity
 - The golden-brown signifies rich organically nurtured soil
 - The green leaf symbolizes organic growth untouched by chemicals
- This emblem assures consumers of compliance with India's national organic standards (FiBL & IFOAM, 2025).

Current Status and Challenges

India ranks second in global organic area (4.74 million ha) and holds the top position in the number of producers (FiBL & IFOAM, 2025). Yet, adoption of organic seed remains low due to:

- Absence of dedicated seed production zones
- Limited farmer training and certification access
- High cost of certification
- Dominance of hybrid seeds from corporate players
- Inadequate integration between R&D and farmers (Chandra et al., 2021)

Government Support and Initiatives

- **Paramparagat Krishi Vikas Yojana (PKVY)** – Encourages seed saving and organic clusters
- **MOVCDNER** – Promotes organic value chains in NE India
- **ICAR/KVK Seed Hubs** – Pilot organic seed production (APEDA, 2020c)
- **National Seed Policy (2002)** – Promotes participatory and decentralized breeding

Way Forward**1. Decentralized Seed Systems**

Promote region-specific seed banks and cooperatives

2. Research and Breeding for Organic Systems

Use Organic Plant Breeding (OPB) focused on natural competitiveness and environmental adaptation (Sripathy et al., 2012)

3. Simplify Certification

Use PGS-India to improve affordability and access

4. Integrate Policy with Practice

National strategies must include organic seed security and market incentives

5. Capacity Building and Outreach

Train farmers in certification, pest management, and seed saving (Fernandez, 2001)

Conclusion

Organic seed production is foundational for resilient and sustainable food systems. In India, with its deep-rooted ecological traditions, the organic seed sector offers a path toward seed sovereignty, biodiversity conservation, and climate-resilient farming. With strong institutional support, participatory breeding, and policy alignment, India can become a global leader in organic seed certification and production.

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FISH PACKAGING TECHNOLOGIES FOR LONGER SHELF LIFE**Bhargav* and Diri Khalo**

College of Fisheries, G. B. Pant University of Agriculture and Technology (GBPUAT),
Pantnagar Uttarakhand – 263145

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Fish and fishery products are highly perishable due to their high-water activity, near-neutral pH, and high content of unsaturated lipids and non-protein nitrogenous compounds. Therefore, immediate processing and suitable packaging are essential to maintain their safety and quality. At the same time, consumers prefer fresh and minimally processed seafood products that retain their original quality characteristics. This article reviews literature from the past decade on fish packaging technologies used to extend shelf life, including modified atmosphere packaging, vacuum packaging, vacuum skin packaging, active packaging with oxygen scavengers, carbon dioxide emitters, moisture regulators, antioxidant and antimicrobial packaging, intelligent packaging with freshness indicators, time–temperature indicators, leakage indicators, retort pouch processing, and edible films and biodegradable coatings. The review also discusses the combined use of these technologies as multiple hurdles for maximizing the preservation of seafood products, along with relevant food packaging legislation.

Keywords: fish packaging technologies; shelf-life extension; fish and fishery products; modified atmosphere packaging; vacuum packaging; active packaging

Introduction

Fish and fishery products are among the most commercially valuable food commodities due to their high nutritional value and desirable sensory characteristics after cooking. They provide high-quality protein, vitamins, minerals, and unsaturated fats that are beneficial to human health. However, these products are highly perishable because of their high-water activity, near-neutral pH, and specific biochemical composition, making immediate processing and suitable packaging essential for maintaining their safety and quality. At the same time, consumers prefer fresh fish products that undergo minimal processing while retaining their original quality characteristics. In this context, packaging plays a crucial role in protecting fish products during storage, transportation, and distribution, thereby reducing spoilage and extending shelf life (Kontominas *et al.*, 2021).

Causes of spoilage in fish and fishery products**Spoilage Due to Enzymic Autolysis**

Enzymic autolysis is one of the primary mechanisms responsible for the early spoilage of fish and fishery products. Immediately after harvesting, endogenous enzymes present in fish muscle, such as proteases and lipases, begin breaking down proteins and lipids. This autolytic activity occurs more rapidly in seafood than in mammals and poultry because fish muscle has a relatively higher pH, generally ranging from 6.2 to 6.5. Although enzymic autolysis may not initially produce strong off-odors or flavors, it significantly affects the texture of fish flesh by causing softening and loss of firmness. A commonly used biochemical indicator of freshness is the K-value, which is based on the enzymatic degradation of adenine nucleotides from ATP to hypoxanthine (Ozogul *et al.*, 2000).

Low K-values, generally below 20%, indicate fresh and high-quality fish, while values between 20% and 40% represent acceptable quality. K-values above 40% are associated with advanced spoilage and unacceptable fish quality. Because the K-value increases with time and endogenous enzyme activity, it is considered a reliable indicator for assessing the degree of fish freshness and spoilage.

Microbial Spoilage

Microbial spoilage is one of the major causes of quality deterioration in fish and fishery products during storage. The microbial flora of fish commonly includes *Pseudomonas*, *Shewanella*, *Vibrio*, *Moraxella*, *Alcaligenes*, *Serratia*, and *Micrococcus* species, depending on the aquatic environment. During storage, these microorganisms proliferate and produce enzymes that break down proteins and lipids, resulting in the formation of volatile compounds such as alcohols, carbonyl compounds, organic acids, sulfur compounds, and nitrogenous compounds. These metabolites are responsible for the development of unpleasant off-odors and off-flavors characteristic of spoiled fish. Chemical indices such as trimethylamine (TMA) and total volatile basic nitrogen (TVB-N) are commonly used to evaluate the degree of microbial spoilage, as they increase with protein decomposition (Hopkins *et al.*, 2020). In addition, biogenic amines such as histamine may accumulate under improper storage conditions and are important indicators of both quality deterioration and potential safety concerns.

Oxidation and Hydrolysis

Lipid oxidation and hydrolysis are important chemical processes responsible for quality deterioration in fish and fishery products, especially in fatty fish such as salmon, mackerel, and sardines. Fish lipids are rich in polyunsaturated fatty acids, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are highly susceptible to oxidation. During oxidation, oxygen reacts with the double bonds of fatty acids to form hydroperoxides, which further decompose into aldehydes and ketones that produce rancid off-odors and flavors (Kasaai *et al.*, 2025). Malondialdehyde (MDA), measured by the thiobarbituric acid (TBA) test, is commonly used as an indicator of lipid oxidation in fish. Hydrolysis occurs through enzymatic and non-enzymatic reactions, with lipases breaking down triglycerides into free fatty acids and glycerol. The accumulation of free fatty acids increases acidity and can contribute to protein denaturation, further reducing the quality of fish products. Together, oxidation and hydrolysis significantly affect the sensory properties, nutritional value, and overall shelf life of seafood.

Fish Packaging Technologies for Longer Shelf Life

Packaging refers to enclosing products in containers such as pouches, bags, trays, cans, bottles, or boxes to provide containment, protection, preservation, utility, and communication. In the case of fish and fishery products, packaging is especially important because these products are highly perishable and susceptible to spoilage, contamination, and physical damage. Effective packaging helps protect fish from physicochemical and microbiological changes, as well as from oxygen, light, moisture, odors, and biological contamination, thereby maintaining product quality and safety. With advancements in packaging science, packaging has evolved from a passive barrier into an active and interactive system that can enhance preservation and extend shelf life (Brody *et al.*, 2008). Technologies such as modified atmosphere packaging, vacuum packaging, active packaging, and intelligent packaging are widely applied to fish and fishery products to improve freshness, reduce spoilage, and support longer shelf life.

Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging (MAP) is a packaging technique in which the atmosphere surrounding the food is modified using specific gases to achieve a desired composition. In fish and fishery products, MAP helps inhibit lipid oxidation, reduce the growth of aerobic spoilage microorganisms, and extend shelf life. The product is usually packed in gas-barrier packaging materials along with controlled mixtures of gases, commonly oxygen (O₂), carbon dioxide (CO₂), and nitrogen (N₂), selected according to the product type, storage conditions, and desired shelf life. Carbon dioxide acts as an antimicrobial agent by lowering pH in aqueous media, nitrogen helps prevent oxidation in oxygen-sensitive foods, and oxygen levels are adjusted based on the requirements for microbial control and product quality. MAP is generally more effective at low temperatures and is widely used for low-fat fish, shellfish, and fatty fish with different gas combinations. However, careful temperature control and suitable packaging materials with appropriate gas permeability are essential to prevent the growth of anaerobic pathogens and ensure both product safety and quality. Overall, MAP is an effective and economical technology for extending the shelf life of fish and fishery products, particularly when combined with other preservation hurdles such as refrigeration.

Vacuum Packaging and Vacuum Skin Packaging

Vacuum packaging (VP) is a packaging technique in which air is removed from the package before sealing, thereby reducing oxygen levels and limiting the growth of aerobic spoilage organisms. This reduction in oxygen also slows oxidative changes, helping to maintain the quality and freshness of fish and fishery products. Effective VP requires packaging materials with high gas and moisture barrier properties, such as multilayer films containing PET, PA, EVOH, or PVdC. VP is particularly useful for frozen fish products because the exclusion of air reduces freezer burn and dehydration, especially in fatty fish such as salmon and mackerel. A related application is sous vide processing, where food is vacuum packed, pasteurized, chilled, and stored under refrigeration, resulting in improved sensory quality and extended shelf life. Vacuum skin packaging (VSP) is an advanced form of VP in which a heated plastic barrier film tightly conforms to the surface of the product, forming a second skin. VSP minimizes headspace, reduces liquid exudation, improves product appearance, and is especially suitable for sliced fish products and frozen seafood. However, because VP and VSP create low-oxygen conditions, strict temperature control is essential to prevent the potential growth of anaerobic pathogens such as *Clostridium botulinum*.

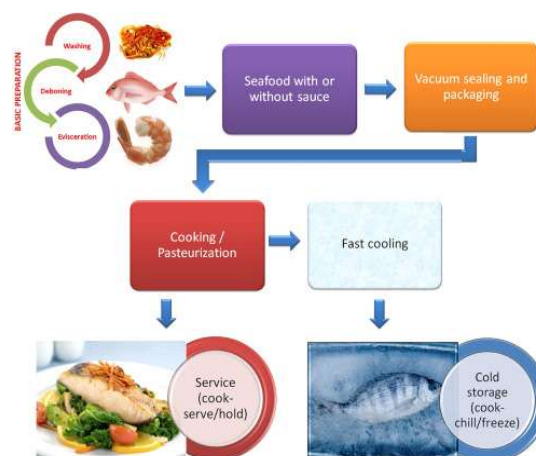


Figure 1. Flow diagram of vacuum-packaged seafood processing and storage.

Active Packaging

Active packaging (AP) refers to packaging systems that provide functions beyond the traditional inert barrier by interacting with the packaged product and its surrounding environment. The main objective of AP is to extend shelf life, improve safety, and maintain the sensory quality of food products, including fish and fishery products. This is achieved by incorporating active compounds

into the packaging material or package interior, where they can perform specific functions such as antioxidant activity, antimicrobial action, moisture control, or gas regulation. Active packaging systems may operate by scavenging unwanted substances, such as oxygen, carbon dioxide, moisture, odors, and ethylene, or by releasing beneficial compounds, including carbon dioxide, ethanol, flavors, antimicrobials, and antioxidants. These active agents can be incorporated into sachets, labels, coatings, or directly into the packaging material through processes such as extrusion or lamination. In fishery products, common applications of active packaging include oxygen scavengers, moisture absorbers, carbon dioxide emitters, and antimicrobial or antioxidant release systems, all of which contribute to preserving product quality and extending shelf life.

Intelligent Packaging

Intelligent packaging (IP) refers to packaging systems that contain indicators or sensors capable of providing information about the history, condition, and quality of packaged food products (Yam *et al.*, 2005). In fish and fishery products, intelligent packaging can monitor important parameters such as freshness, gas leakage, microbial contamination, and temperature exposure during storage and distribution. These indicators may be placed inside or outside the package and are designed to respond to specific changes in the product or its environment. By providing visible and often irreversible signals, intelligent packaging helps consumers and producers assess the actual shelf life and current quality status of seafood products. The main categories of intelligent packaging include freshness indicators, which detect quality changes related to spoilage; time-temperature indicators, which monitor temperature history; and leakage indicators, which identify package integrity problems.

Safety Considerations in Vacuum and Modified Atmosphere Packaging

Vacuum packaging (VP) and modified atmosphere packaging (MAP) are effective technologies for extending the shelf life of fishery products, but their use under refrigerated conditions also requires careful attention to food safety. The main concern is the potential growth and toxin production of non-proteolytic *Clostridium botulinum* types B, E, and F, which are associated with fishery products and can grow at low temperatures under reduced-oxygen conditions. Botulinum toxin may be produced before spoilage becomes apparent to consumers, making strict control measures essential. Regulatory recommendations emphasize that VP and MAP should be used for refrigerated raw fishery products only when supported by a detailed HACCP plan, high-quality raw fish, continuous storage and distribution at temperatures ≤ 3.3 °C, and assurance that sensory rejection occurs before toxin formation. Additional preventive measures, such as appropriate labeling and other secondary safety controls, should also be applied. Similar safety requirements are recognized in European food safety regulations, highlighting the importance of temperature control and hazard management in VP and MAP seafood products.

Food-Grade Packaging Materials

Fish packaging materials should be suitable for direct contact with food and should not contain toxic substances. Food-grade materials help protect fish products from contamination, moisture loss, oxygen exposure, and physical damage. Common materials include multilayer films, PET, PA, EVOH, and other approved packaging polymers. The use of safe packaging materials helps maintain the quality, freshness, and safety of fishery products.

Temperature Control and Cold Chain Management

Fish and fishery products are highly perishable and require strict temperature control during storage and transportation. Proper refrigeration slows microbial growth, enzymatic activity, and

biochemical spoilage. Maintaining an uninterrupted cold chain is especially important for vacuum-packaged and modified atmosphere-packaged seafood products. Effective cold-chain management helps preserve product quality, extend shelf life, and reduce the risk of foodborne illness.

Safety of Vacuum Packaging (VP) and Modified Atmosphere Packaging (MAP)

Vacuum packaging and modified atmosphere packaging create low-oxygen conditions that can inhibit aerobic spoilage microorganisms. However, these conditions may also favor the growth of anaerobic pathogens such as *Clostridium botulinum* if temperature control is not properly maintained. Therefore, VP and MAP products require strict refrigeration, validated shelf-life studies, and HACCP-based safety controls. Proper monitoring and handling ensure that these packaging technologies remain safe and effective for seafood preservation.

Active and Intelligent Packaging Regulations

Active packaging (AP) and intelligent packaging (IP) systems play an important role in enhancing the quality, safety, and shelf life of fish and fishery products. These advanced packaging systems must comply with food-contact regulations to ensure consumer safety. Packaging materials and active components are regulated to prevent the migration of harmful substances into food that may affect human health, food composition, or sensory characteristics. Proper labeling, safety information, and compliance testing are required for packaging materials containing active or intelligent components. Edible films and coatings used in active packaging should also meet food safety standards, follow good manufacturing practices, and support environmentally sustainable packaging approaches. These regulations help ensure the safe and effective application of advanced packaging technologies in seafood preservation.

Conclusions

Packaging technologies have progressed from simple protective barriers to advanced systems that help maintain the quality, safety, and shelf life of fish and fishery products. Conventional methods such as modified atmosphere packaging (MAP), vacuum packaging (VP), vacuum skin packaging, and retort pouch processing have been widely applied for seafood preservation. Advanced approaches, including active packaging systems with oxygen scavengers, antimicrobial agents, and antioxidant materials, further enhance freshness and product stability. Intelligent packaging technologies, such as freshness indicators and time-temperature indicators, allow monitoring of seafood quality during storage and distribution. In addition, the development of biodegradable and bio-based packaging materials is gaining importance due to increasing environmental concerns. Future fish packaging technologies should focus on improving shelf life, safety, sensory quality, sustainability, and regulatory compliance for effective commercial application.

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INTEGRATED PEST MANAGEMENT OF YELLOW STEM BORER: HEALTHY RICE, PROTECTED FARMERS, AND A PROSPEROUS FUTURE

**Sudhir Kumar Mishra¹, Aditya Kumar Sharma^{2*}, Shailendra Kumar Mishra³,
Ankit Kumar⁴ and Abhishek Kumar Yadav⁵**

¹Assistant Professor, Department of Horticulture,
National Post Graduate College Barhalganj 273402, Uttar Pradesh, India

²Research scholar, Department of Ag. Entomology,
B.R.D. PG. College Deoria- 274001, Uttar Pradesh, India

³Subject Matter Specialist, Entomology/Nematology,
Krishi Vigyan Kendra, Kotwa Azamgarh I -276207, Uttar Pradesh, India

⁴Research scholar, Department of Ag. Entomology,
A.N.D.U.A & T, Kumarganj-224229, Ayodhya, Uttar Pradesh, India

⁵Research scholar, Department of Ag. Entomology,
C.S.A.U.A & T, Kanpur- 208002, Uttar Pradesh, India

*Corresponding Email: adisharmajmd098@gmail.com

Abstract

The yellow stem borer is one of the most destructive insect pests of rice. It causes dead heart symptoms during the vegetative stage and white ear symptoms during the reproductive stage, leading to substantial yield losses. Effective and sustainable management of this pest cannot be achieved by relying solely on chemical insecticides. Instead, it requires the adoption of an Integrated Pest Management (IPM) approach. Regular field monitoring, balanced nutrient and water management, field sanitation, pheromone traps, biological control, and the judicious use of recommended insecticides only when necessary can effectively suppress yellow stem borer populations. By adopting these integrated strategies, farmers can reduce production costs, improve grain yield and quality, and ensure environmentally sustainable rice cultivation.

Keywords: Yellow Stem Borer, Rice Protection, Integrated Pest Management, Sustainable Agriculture and Biological Pest Control

Introduction

Rice (*Oryza sativa* L.) is one of the oldest and most important food crops in the world. In India and many other Asian countries, rice is not merely an agricultural crop but a cornerstone of food security, culture, tradition, and the livelihood of millions of people. It occupies a prominent place in the Indian diet and provides a major share of the daily energy requirements for more than half of the country's population. India is the world's second-largest producer of rice and contributes significantly to global rice production. Rice is cultivated over approximately 47–48 million hectares, with an annual production exceeding 140 million tonnes. Major rice-producing states include Uttar Pradesh, West Bengal, Punjab, Chhattisgarh, Odisha, Telangana, Andhra Pradesh, Tamil Nadu, Bihar, and Assam. In Uttar Pradesh, rice is the principal kharif crop and serves as a major source of income and livelihood for millions of farming families.

Rice is not only a staple food but also an important source of nutrition. It primarily contains 70–80% carbohydrates, which provide instant energy to the human body. In addition, rice contains approximately 6–8% protein, B-group vitamins (particularly thiamine, niacin, and riboflavin),

essential minerals, and a small amount of fat. Brown rice is comparatively richer in dietary fiber, antioxidants, and micronutrients. Rice by-products such as husk, straw, and bran are widely utilized as livestock feed, mushroom cultivation substrate, organic manure, bio energy feedstock, raw material for the paper industry, and in several other agro-based industries. Thus, rice cultivation extends beyond food production and plays a vital role in strengthening the rural economy, generating employment, and supporting agricultural industries. Although scientific innovations, improved cultivars, and modern crop production technologies have significantly enhanced rice productivity, insect pests and diseases continue to be major constraints to production. Scientific studies indicate that the combined effect of insect pests, diseases, and weeds can reduce rice yield by 25–40%. Among these factors, insect pests are particularly important because they attack the crop at different growth stages, directly reducing both grain yield and quality. Rice is attacked by several economically important insect pests, including the yellow stem borer, brown plant hopper, rice Earhead bug, leaf folder, gall midge, and rice hispa. Among these, the yellow stem borer is regarded as the most destructive and economically significant pest. It occurs in almost all rice-growing regions of India and causes substantial economic losses every year. Under favourable environmental conditions, failure to manage this pest in time may result in 20–80% yield loss.

Nature of Damage

The larval stage of the yellow stem borer is the most destructive. The adult moth does not feed on the crop but lays eggs on rice leaves. After hatching, the young larvae remain on the leaf surface for a short period before boring into the stem. Inside the stem, they feed on the soft internal tissues and continue their development while remaining protected. Because the larvae remain concealed within the stem, they are not effectively controlled by contact insecticides. Consequently, farmers often fail to achieve satisfactory control even after repeated insecticide applications. The nature of damage caused by the yellow stem borer varies with the growth stage of the rice crop. During the vegetative stage, the larvae bore into the stem and feed on the growing tissues, destroying the central shoot. As a result, the central leaf dries up and can be easily pulled out. This characteristic symptom is commonly known as "dead heart." Plants exhibiting dead heart symptoms fail to produce new growth, resulting in a reduction in the number of productive tillers and ultimately lowering grain yield.



Figure:1. Larva of Yellow Stem Borer (*Scirpophaga incertulas*) most destructive stage

When infestation occurs during the reproductive stage, particularly after panicle initiation, the larvae damage the developing panicle inside the stem. Consequently, the emerging panicles remain completely white and fail to produce grains, or produce only a few poorly developed grains. This symptom is known as "white ear" or "white head."

The white ear stage causes the greatest economic loss because the crop appears healthy and green from the outside, giving the impression of a normal field. However, the panicles remain sterile due to the absence of grain formation, resulting in substantial reductions in final yield.



Figure:2. Pupa of the Yellow Stem Borer (Resting stage)

Why is Integrated Pest Management (IPM) Necessary?

A unique characteristic of the yellow stem borer is that its larvae remain concealed inside the rice stem while feeding. As a result, the infestation is difficult to detect during the early stages. By the time visible symptoms appear, considerable damage has already occurred. Therefore, relying solely on chemical insecticides is not a sustainable solution for managing this pest. Effective and long-term management requires the adoption of the scientific principles of Integrated Pest Management (IPM). This approach combines regular field monitoring, timely pest detection, balanced crop nutrition, cultural practices, pheromone trapping, biological control, conservation of natural enemies, and the judicious use of recommended insecticides only when necessary.

Integrated Pest Management of Yellow Stem Borer

1. Regular Field Monitoring and Timely Detection

Regular field monitoring is the first and most important step in the successful management of yellow stem borer. Farmers should begin inspecting their fields 20–25 days after transplanting and continue monitoring at least once every week. During field inspection, observations should be made at different locations within the field. Particular attention should be given to the presence of dead heart, white ear, egg masses on leaves, and adult moth activity. Early detection enables effective pest management with lower costs and reduced crop damage. In contrast, delayed detection allows the larvae to enter the stem, making control measures much less effective.

2. Cultural Management Practices

Cultural practices form the foundation of Integrated Pest Management. A healthy and well-managed crop is generally less susceptible to insect pest infestation. Therefore, farmers should always use certified, healthy seed and cultivate recommended or tolerant rice varieties suited to local agro-climatic conditions. Timely transplanting helps reduce the impact of successive generations of the yellow stem borer, whereas delayed transplanting often results in greater pest infestation. Proper spacing between plants should also be maintained to ensure adequate air circulation and sunlight penetration. Excessively dense plant populations create humid conditions that favour pest development. After harvest, rice stubbles, infested stems, and other crop residues should be removed and destroyed, as they serve as overwintering sites for larvae and pupae, becoming a source of infestation in the following season. Deep ploughing exposes the hidden pupae to sunlight and predatory birds, thereby reducing their survival. In addition, effective weed management in both the field and bunds is essential because several weed species act as alternate hosts for the yellow stem borer.

3. Balanced Nutrient and Water Management

Balanced nutrient and water management plays a crucial role in minimizing yellow stem borer infestation. Excessive application of nitrogen fertilizers encourages pest development by producing soft, succulent plant tissues that are more attractive to larvae. Therefore, the recommended dose of nitrogen should not be applied all at once; instead, it should be split into appropriate applications according to crop requirements. In addition to nitrogen, phosphorus, potassium, and zinc should also be supplied in balanced amounts. Adequate potassium strengthens plant cell walls, thereby enhancing the crop's tolerance to stem borer attack and reducing the severity of infestation. Proper water management is equally important. Continuous water logging should be avoided, and irrigation and drainage should be managed according to crop requirements. Periodic removal of excess water from the field creates less favourable conditions for pest survival and multiplication, thereby contributing to effective pest management.

4. Mechanical and Physical Control

Mechanical and physical methods are among the simplest and most effective approaches for suppressing yellow stem borer during its early stages. During routine field inspections, egg masses found on rice leaves should be collected and destroyed. Similarly, plants exhibiting dead heart symptoms should be uprooted and removed from the field to eliminate larvae before they spread further. The use of light traps at night is also an effective method for attracting and destroying adult moths. Reducing the adult moth population helps minimize mating and decreases the likelihood of subsequent generations developing in the field.

5. Management through Pheromone Traps

Pheromone traps provide an environmentally friendly and highly effective technique for monitoring and managing adult male yellow stem borer moths. Approximately 20–25 days after transplanting, 10–12 pheromone traps per hectare should be installed. The pheromone lure should be replaced every 20–25 days to maintain trapping efficiency. These traps release a synthetic sex pheromone that mimics the natural scent emitted by female moths, thereby attracting male moths. By reducing male–female mating, pheromone traps decrease egg laying and suppress the pest population. In addition, the number of moths captured in the traps provides a reliable indication of the pest population, enabling timely management decisions.

6. Biological Control

Natural enemies play an essential role in regulating yellow stem borer populations under field conditions. Beneficial organisms such as spiders, dragonflies, damselflies, and predatory beetles should be conserved by avoiding unnecessary and repeated applications of chemical insecticides. Egg parasitoids such as *Trichogramma japonicum* and *Trichogramma chilonis* are highly effective biological control agents against the yellow stem borer. Beginning about 30 days after transplanting, Trichocards containing approximately 50,000–100,000 parasitized eggs per hectare should be released 4–6 times at intervals of 7–10 days. These parasitoids destroy the pest eggs before the larvae emerge, thereby preventing further crop damage.

7. Botanical and Bio-pesticide Management

Neem-based bio pesticides are particularly useful during the early stages of infestation. Spraying Azadirachtin (1500 ppm or 10000 ppm) at the recommended dose adversely affects the feeding and development of newly hatched larvae. Although neem-based products are generally ineffective against fully developed larvae already concealed within the stem, their timely application during the early stages of infestation can reduce pest establishment and lessen the dependence on chemical insecticides.

8. Chemical Control

Chemical control should be adopted only when the infestation exceeds the Economic Threshold Level (ETL). In rice, chemical intervention is recommended when 5% dead hearts are observed during the vegetative stage or 2% white ears are observed during the reproductive stage. For effective control, spray Chlorantraniliprole 18.5 SC @ 150 ml/ha or Flubendiamide 39.35 SC @ 50 ml/ha diluted in 500–600 litres of water per hectare, ensuring uniform coverage of the crop. Alternatively, Chlorantraniliprole 0.4 GR @ 10 kg/ha may be applied uniformly in the field and has also been found highly effective against yellow stem borer.

Conclusion

Yellow stem borer is one of the most destructive insect pests of rice and can cause severe yield losses if not managed properly. Sustainable management cannot be achieved through chemical insecticides alone. An integrated approach involving regular monitoring, cultural practices, balanced nutrient and water management, mechanical control, pheromone trapping, biological control, botanical pesticides, and neem-based chemical control is essential for effective and eco-friendly management. Adoption of Integrated Pest Management (IPM) not only reduces pest damage but also lowers production costs, improves grain yield and quality, conserves beneficial organisms, minimizes environmental pollution, and promotes sustainable rice cultivation. By implementing these integrated strategies, farmers can achieve healthy rice crops, better profitability, safer food production, and long-term agricultural sustainability.

MARKER-ASSISTED BACKCROSS BREEDING: BRIDGING TRADITIONAL AND MOLECULAR PLANT BREEDING

Priyanshu Singh

PhD Research Scholar, Department of Genetics and Plant Breeding,
Acharya Narendra Deva University of Agriculture and Technology,
Ayodhya, Uttar Pradesh, India
Corresponding Email: singhpriyanshu1818@gmail.com

Introduction

Agriculture has entered a new era where increasing food production is no longer the only objective. Farmers today must produce more food while coping with climate change, shrinking arable land, emerging pests and diseases, water scarcity, and the growing demand for nutritious crops. According to the United Nations, the global population is expected to reach nearly 9.7 billion by 2050, placing immense pressure on agricultural systems to ensure food and nutritional security. Under these circumstances, plant breeding has become one of the most important scientific disciplines for developing crop varieties that are high yielding, resilient, and adaptable to changing environmental conditions.

Advances in molecular biology and biotechnology have transformed this scenario. The discovery of molecular markers has enabled breeders to identify desirable genes directly at the DNA level, eliminating much of the uncertainty associated with conventional selection. Among the molecular breeding approaches developed over the past three decades, Marker-Assisted Backcross Breeding (MABB) has emerged as one of the most successful and widely adopted techniques. Rather than replacing traditional breeding, MABB strengthens it by combining classical breeding principles with the precision of molecular genetics. This integration allows breeders to improve elite crop varieties more rapidly while preserving the characteristics that farmers and consumers value most.

Why Conventional Backcross Breeding Has Limitations

One of the major limitations of conventional breeding is that selection depends primarily on visible plant characteristics. Traits such as disease resistance, drought tolerance, or grain quality are often difficult to identify accurately during the early stages of plant growth. Many economically important traits are expressed only under specific environmental conditions, forcing breeders to wait until plants mature before making selection decisions.

Another significant challenge is linkage drag. Genes are inherited as chromosome segments rather than as isolated units. Consequently, when a desirable gene is transferred from a donor parent, neighboring undesirable genes may also be inherited. These unwanted genes can reduce yield, delay maturity, or adversely affect grain quality. Conventional breeding provides little opportunity to identify and eliminate these unwanted chromosome segments efficiently.

Furthermore, recovering the genetic background of the recurrent parent requires repeated backcrossing over many years. For crops with long generation times, this significantly delays the release of improved varieties.

What is Marker-Assisted Backcross Breeding?

Marker-Assisted Backcross Breeding is a molecular breeding strategy used to transfer one or a few desirable genes or quantitative trait loci (QTLs) from a donor parent into a superior cultivar while

recovering almost the entire genetic background of the recurrent parent. DNA markers linked to the target gene enable breeders to monitor its inheritance during every generation of breeding.

The primary objective of MABB is simple: improve the weakness of an elite variety without changing its identity.

The Three Components of Marker-Assisted Backcross Breeding

The success of MABB depends on three complementary selection strategies that together ensure accuracy and efficiency.

Foreground Selection- Foreground selection identifies plants carrying the target gene or QTL using molecular markers closely linked to that gene. For example, when transferring the Sub1 gene for flood tolerance into rice, breeders use DNA markers associated with the Sub1 locus to identify seedlings possessing the desired gene. This eliminates the need to expose every plant to flooding during selection.

Recombinant Selection- The second component, recombinant selection, minimizes linkage drag. Molecular markers located on both sides of the target gene help breeders identify plants where recombination has removed unnecessary donor chromosome segments while retaining the desired gene. This ensures that unwanted traits are not transferred along with the target gene.

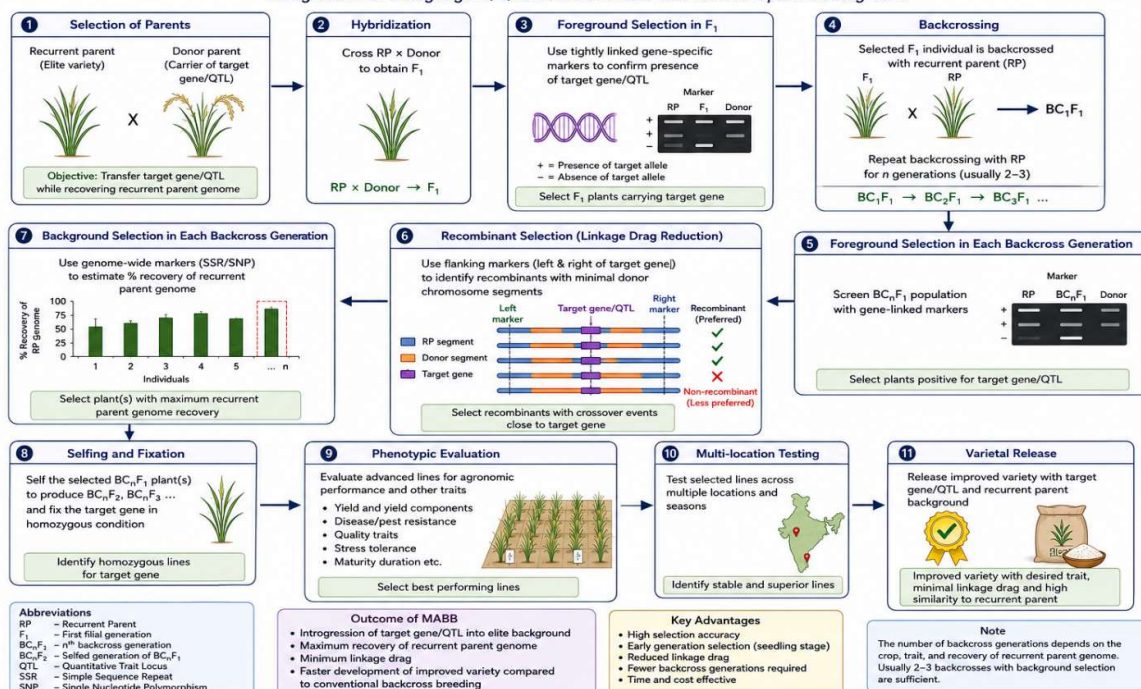
Background Selection- Background selection uses markers distributed throughout the genome to estimate how much of the recurrent parent's DNA has been recovered after each backcross generation. Plants possessing the highest proportion of recurrent parent DNA are selected for further breeding. This greatly accelerates the recovery of the elite variety while preserving its agronomic characteristics.

The MABB Workflow

Although MABB relies on advanced molecular tools, its breeding process follows a logical sequence. First, breeders identify an elite recurrent parent and a donor parent carrying the desired gene. These parents are crossed to produce F₁ hybrids, which are confirmed using molecular markers.

The selected hybrids are then repeatedly backcrossed with the recurrent parent. During each generation, foreground selection confirms the presence of the target gene, recombinant selection reduces unwanted donor DNA around the target region, and background selection identifies plants that most closely resemble the recurrent parent genetically.

Once sufficient recovery of the recurrent parent genome has been achieved, the selected plants are self-pollinated to produce homozygous lines. These lines undergo rigorous field testing for yield, disease resistance, grain quality, and environmental adaptation before they are recommended for release.

Workflow of Marker-Assisted Backcross Breeding (MABB)*Introgression of a target gene/QTL from donor into elite recurrent parent background***A Real-World Example: Swarna-Sub1 Rice**

Perhaps the most celebrated success story of Marker-Assisted Backcross Breeding is the development of Swarna-Sub1, a flood-tolerant version of the popular rice variety Swarna. Swarna has long been favored by farmers in eastern India because of its high yield, excellent grain quality, and broad adaptability. However, prolonged flooding during the monsoon often caused severe crop losses because the variety lacked submergence tolerance.

Researchers at the International Rice Research Institute (IRRI), in collaboration with the Indian Council of Agricultural Research (ICAR) and national breeding programs, addressed this problem by transferring the Sub1 quantitative trait locus from the traditional rice landrace FR13A into Swarna using Marker-Assisted Backcross Breeding.

Foreground markers identified plants carrying the Sub1 gene, recombinant selection minimized unwanted donor DNA, and background selection rapidly restored the Swarna genome. The resulting variety retained the agronomic and grain-quality characteristics that farmers preferred while gaining the ability to survive complete submergence for nearly two weeks.

The success of Swarna-Sub1 illustrates the fundamental advantage of MABB: rather than replacing a popular variety, breeders improved its weakest characteristic while preserving its identity. This achievement has benefited millions of farmers across flood-prone regions of India and neighboring countries, demonstrating how molecular biology can provide practical solutions to real agricultural problems.

Ground-Level Success Stories: When Molecular Breeding Reaches Farmers

The true success of any plant breeding technology is measured not in research laboratories but in farmers' fields. Marker-Assisted Backcross Breeding (MABB) has demonstrated its value by

developing improved crop varieties that address real agricultural challenges while retaining the characteristics farmers and consumers already prefer. Unlike many advanced technologies that remain confined to research institutions, MABB has been successfully integrated into national breeding programmes and adopted across millions of hectares, particularly in developing countries where food security is a major concern.

One of the reasons for the widespread acceptance of MABB is that it focuses on improving existing, well-adapted varieties rather than replacing them entirely. Farmers often hesitate to adopt completely new cultivars because they are uncertain about their grain quality, market acceptance, maturity period, or agronomic performance. MABB overcomes this barrier by introducing only the desired trait into an already popular variety, ensuring minimal changes in its overall characteristics.

Improved Samba Mahsuri: Combining Grain Quality with Disease Resistance

One of the best examples of successful MABB is the improvement of Samba Mahsuri (BPT 5204), one of India's most popular fine-grain rice varieties. It is highly valued for its excellent cooking quality, aroma, and market demand, making it a preferred choice among farmers and consumers. However, the variety is highly susceptible to bacterial blight, a devastating disease caused by *Xanthomonas oryzae* pv. *oryzae*, which can reduce grain yield by as much as 50–70% under severe infection.

Instead of replacing Samba Mahsuri with another resistant variety, scientists at the ICAR–Indian Institute of Rice Research (IIRR) and collaborating institutions adopted Marker-Assisted Backcross Breeding to improve it. Three major bacterial blight resistance genes—Xa21, xa13, and xa5—were introgressed into the genetic background of Samba Mahsuri. Molecular markers were used throughout the breeding process to ensure that only plants carrying all three resistance genes and the maximum recurrent parent genome were selected.

The resulting variety retained the same grain quality, cooking characteristics, and maturity duration as the original Samba Mahsuri while exhibiting durable resistance to bacterial blight. Farmers benefited from reduced crop losses and lower dependence on chemical pesticides, while consumers continued to enjoy the rice quality they preferred. This achievement remains one of the most successful examples of gene pyramiding through Marker-Assisted Backcross Breeding.

Applications of MABB in Wheat Improvement

Marker-Assisted Backcross Breeding has enabled researchers to transfer important resistance genes such as Lr (Leaf Rust), Yr (Yellow Rust), and Sr (Stem Rust) into elite wheat cultivars without compromising their yield potential or grain quality. In India, molecular markers have been used to improve popular wheat varieties by incorporating disease resistance while preserving farmer-preferred agronomic traits. Research is also underway to introgress quantitative trait loci associated with drought tolerance, heat tolerance, and improved root architecture, helping wheat maintain productivity under increasingly unpredictable climatic conditions.

The Future of Marker-Assisted Backcross Breeding

The future of plant breeding lies in integrating Marker-Assisted Backcross Breeding with other emerging technologies rather than using them independently. One of the most promising developments is Genomic Selection (GS), which uses thousands of molecular markers distributed across the genome to predict the breeding value of plants. While MABB is ideal for transferring

major genes, genomic selection is particularly effective for improving complex quantitative traits. Recent advances in high-throughput phenotyping are also complementing molecular breeding. Drones, multispectral imaging, thermal cameras, and automated sensors allow breeders to evaluate thousands of plants rapidly for physiological traits such as canopy temperature, biomass accumulation, and water-use efficiency. These technologies improve the accuracy of selection while reducing labor requirements. Perhaps the most revolutionary development is CRISPR-Cas genome editing. Unlike MABB, which transfers genes from donor parents, CRISPR enables scientists to modify genes directly within elite cultivars.

Artificial Intelligence (AI) is expected to further accelerate molecular breeding. Machine learning algorithms can analyze large genomic and phenotypic datasets, predict superior parental combinations, identify important marker-trait associations, and optimize breeding strategies.

India's Contribution to Marker-Assisted Backcross Breeding

India has emerged as one of the global leaders in the application of Marker-Assisted Backcross Breeding. Institutions such as the Indian Council of Agricultural Research (ICAR), ICAR–Indian Agricultural Research Institute (IARI), ICAR–Indian Institute of Rice Research (IIRR), International Rice Research Institute (IRRI) South Asia Regional Centre, and numerous State Agricultural Universities have played pivotal roles in developing improved crop varieties through molecular breeding.

The successful development of Swarna-Sub1, Improved Samba Mahsuri, bacterial blight-resistant rice, drought-tolerant rice, and rust-resistant wheat demonstrates India's growing expertise in integrating molecular biology with conventional breeding. Government initiatives promoting climate-resilient agriculture and genomics-based crop improvement continue to strengthen research in this field.

Conclusion

MABB enables breeders to transfer desirable genes rapidly while preserving the elite characteristics of widely accepted crop varieties. The technology has shortened breeding cycles, reduced linkage drag, improved selection accuracy, and accelerated the development of climate-resilient and disease-resistant crops.

Ground-level success stories such as Swarna-Sub1 and Improved Samba Mahsuri demonstrate that MABB is not merely a laboratory innovation but a practical tool that directly benefits farmers through increased productivity, reduced production risks, and improved economic returns. Its contribution to sustainable agriculture extends beyond yield improvement by reducing pesticide use, conserving natural resources, and enhancing resilience to climate change.

In an era characterized by rapid climate change, increasing food demand, and limited natural resources, Marker-Assisted Backcross Breeding truly serves as a bridge between traditional plant breeding and modern molecular biology. Its continued application will play a vital role in achieving global food security, improving farmers' livelihoods, and building resilient agricultural systems for future generations.

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FORENSIC ENTOMOLOGY: THE ROLE OF INSECTS IN CRIME INVESTIGATION

Lingutla Geethanjali¹, Mood Suguna² and Narne Kavya³

¹Vignan's Foundation for Science, Technology & Research (VFSTR),
Vadlamudi, Guntur - 522213, Andhra Pradesh

²Department of Entomology, College of Agriculture,
Sardar Vallabhbhai Patel University of Agriculture and Technology,
Meerut - 250341, Uttar Pradesh, India.

³Govind Ballabh Pant University of Agriculture and Technology (GBPUAT),
Pantnagar – 263145, Uttarakhand, India
Corresponding Email: lingutlageethanjali55@gmail.com

Introduction

Crime investigation is commonly associated with fingerprints, DNA profiling, surveillance cameras, and forensic laboratories. However, one of the most remarkable yet often overlooked sources of evidence comes from insects. These tiny organisms are among the first to colonize a dead body and can provide valuable information about the circumstances surrounding death. By studying the insect species present and their developmental stages, forensic scientists can estimate the post-mortem interval (PMI), determine whether a body has been moved, and gather crucial evidence to assist criminal investigations (Byrd and Castner, 2010).

Forensic entomology is the branch of science that applies the study of insects and other arthropods to legal investigations. When a body begins to decompose, insects such as blow flies and flesh flies are attracted within minutes or hours to lay their eggs. As these insects develop through predictable life stages, forensic entomologists use their growth patterns to estimate the time since death with considerable accuracy. Besides determining the post-mortem interval, insects can also provide clues about the place of death, presence of wounds, and cases involving neglect or abuse (Catts and Goff, 1992; Amendt *et al.*, 2007).

With advancements in science and technology, forensic entomology has become an indispensable tool in modern criminal investigations. Molecular techniques such as DNA barcoding and artificial intelligence are further improving the accuracy of insect identification and forensic analysis. These developments have transformed insects into silent but reliable witnesses, highlighting their vital role in uncovering the truth and supporting the delivery of justice (Gennard, 2012).

Major Insects Used in Forensic Investigations

Not all insects are associated with a dead body. Only certain groups are attracted to decomposing remains in a predictable sequence, making them valuable indicators in forensic investigations. By identifying these insects and understanding their biology, forensic entomologists can reconstruct events surrounding a person's death. Some of the most important insects used in forensic investigations are described below.

1. Blow Flies (Family: Calliphoridae)

Blow flies are the first insects to arrive at a dead body, often within a few minutes to a few hours after death. Attracted by the odor of decomposition, female blow flies lay eggs on natural body

openings and wounds. The eggs hatch into larvae (maggots), which develop rapidly. Since the growth of these larvae follows a predictable pattern, blow flies are considered the most important insects for estimating the post-mortem interval (PMI) (Byrd and Castner, 2010).

2. Flesh Flies (Family: Sarcophagidae)

Flesh flies also colonize decomposing bodies during the early stages of decomposition. Unlike blow flies, they deposit living larvae instead of eggs, allowing their offspring to begin feeding immediately. Their developmental stages provide additional evidence for estimating the time since death, particularly when blow fly evidence is limited (Catts and Goff, 1992).

3. House Flies (Family: Muscidae)

House flies generally arrive after blow flies and flesh flies, especially during the later stages of decomposition. Although they are less useful for determining the exact time of death, their presence helps investigators understand the progression of decomposition and the environmental conditions surrounding the body.

4. Beetles (Families: Dermestidae, Silphidae and Staphylinidae)

Beetles usually appear during the advanced stages of decomposition when softest tissues have been consumed. Different beetle species feed on dried skin, hair, cartilage, and other remaining tissues. Their presence helps forensic scientists estimate longer post-mortem intervals and determine the stage of decomposition (Gennard, 2012).

5. Ants and Other Predatory Insects

Ants, wasps, and other predatory insects may feed on fly eggs and larvae present on the body. Although they are not primary forensic indicators, they can alter insect succession and affect estimates of the post-mortem interval. Therefore, forensic investigators carefully record their presence at the crime scene.

6. Mites (Subclass: Acari)

Mites are tiny arthropods that are commonly found on decomposing bodies during the later stages of decomposition. Certain mite species are associated with specific stages of decay and can provide supplementary information, particularly in cases involving advanced decomposition.

Modern Technologies in Forensic Entomology

Advances in science and technology have significantly enhanced the accuracy and reliability of forensic entomology. Traditionally, forensic entomologists relied on the physical characteristics of insects for species identification. However, closely related species often appear very similar, making identification difficult. Today, DNA barcoding has become a powerful molecular tool that enables rapid and accurate identification of insect species, even from immature stages such as eggs and larvae or damaged specimens. Accurate species identification is essential because each insect species has a unique developmental rate, which directly influences the estimation of the post-mortem interval (PMI) (Harvey *et al.*, 2003; Wells and Stevens, 2008).

Recent technological developments such as artificial intelligence (AI), digital imaging, and automated insect recognition systems are further transforming forensic investigations. AI-based image analysis can assist experts in identifying insects quickly and accurately, while Geographic Information Systems (GIS) help map insect distribution patterns and environmental conditions at crime scenes. These innovations improve the efficiency of forensic investigations and strengthen the scientific evidence presented in courts of law (Byrd and Castner, 2010).



Challenges and Future Prospects

Despite its immense potential, forensic entomology faces several challenges. The development of insects is strongly influenced by environmental factors such as temperature, humidity, rainfall, and geographical location. Therefore, inaccurate environmental data may lead to errors in estimating the post-mortem interval. Another major challenge is the shortage of trained forensic entomologists and comprehensive databases on insect fauna in many countries. In addition, improper collection or preservation of insect evidence at crime scenes can reduce the accuracy of forensic analyses (Amendt *et al.*, 2007).

The future of forensic entomology is highly promising. Advances in molecular biology, genomics, DNA barcoding, artificial intelligence, and machine learning are expected to improve the speed and precision of insect identification and forensic interpretation. Establishing regional insect databases, developing standardized investigation protocols, and increasing collaboration among entomologists, forensic scientists, and law enforcement agencies will further strengthen the role of forensic entomology in criminal investigations. As technology continues to evolve, insects will remain indispensable biological witnesses in the pursuit of justice.

Conclusion

Forensic entomology has emerged as a valuable scientific discipline that combines entomology with forensic science to assist in criminal investigations. Insects, particularly flies and beetles, provide crucial information about the post-mortem interval, decomposition process, and other circumstances surrounding death. Their predictable patterns of colonization make them reliable biological indicators at crime scenes.

Modern technologies such as DNA barcoding, artificial intelligence, and digital imaging have greatly improved the accuracy and efficiency of forensic investigations. Although challenges related to environmental variation, species identification, and limited expertise still exist, continuous research and technological advancements are expanding the scope of forensic

entomology. As a result, insects are no longer viewed merely as decomposers but as "silent witnesses" that help uncover hidden truths and contribute significantly to the administration of justice.

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CAGE CULTURE: A PROFITABLE AQUACULTURE PRACTICE

Guguloth Harikrishna

Kerala University of Fisheries and Ocean Studies

Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Aquaculture has become one of the fastest-growing food production sectors worldwide, playing a vital role in food security, employment generation, and rural economic development. Among the various culture systems, cage culture has emerged as an efficient and profitable aquaculture practice due to its low land requirement, efficient resource utilization, and high production potential. Cage culture involves rearing fish in floating or fixed enclosures installed in natural or man-made water bodies such as reservoirs, lakes, rivers, dams, and coastal waters. The system allows continuous water exchange, maintains good water quality, and supports high stocking densities, resulting in improved fish growth and production efficiency. Advances in cage design, nutritionally balanced feeds, fish health management, and digital monitoring technologies have further enhanced the sustainability and profitability of cage farming. This article discusses the principles of cage culture, site selection, cage design, suitable fish species, management practices, and its role in promoting sustainable aquaculture and improving farmers' livelihoods.

Keywords: Cage Culture, Aquaculture, Reservoir Fisheries, Fish Farming, Sustainable Aquaculture, Floating Cages, Fish Production.

Introduction

Aquaculture has become an important contributor to global food security by supplying more than half of the aquatic animals consumed by humans worldwide (FAO, 2024). Increasing demand for fish protein, declining capture fisheries, and limited availability of cultivable land have encouraged the development of innovative aquaculture systems capable of producing more fish using existing water resources. Among these systems, cage culture has gained considerable attention because it enables fish production in natural and artificial water bodies without the need for constructing ponds (FAO, 2022). India possesses enormous inland water resources, including reservoirs, lakes, rivers, irrigation canals, and hydropower reservoirs, many of which remain underutilized for fish production. Cage culture provides an opportunity to utilize these water bodies efficiently while generating employment and income for rural communities. The Government of India, through agencies such as the National Fisheries Development Board (NFDB), ICAR, and the Pradhan Mantri Matsya Sampada Yojana (PMMSY), has actively promoted cage farming as an important strategy for increasing inland fish production and improving farmers' livelihoods (ICAR, 2023). Compared with traditional pond aquaculture, cage culture requires relatively low initial land investment, allows easy stock management, facilitates harvesting, and provides better water quality due to continuous water exchange. These advantages have made cage farming one of the fastest-growing aquaculture technologies for both freshwater and marine environments. However, successful cage farming requires proper site selection, scientific stocking density, balanced nutrition, regular health monitoring, and responsible environmental management to ensure sustainable production.

Concept of Cage Culture

Cage culture is an aquaculture system in which fish are reared inside enclosed net structures suspended or floating in natural or man-made water bodies. The cages confine cultured fish while

allowing free exchange of water through the mesh, ensuring a continuous supply of dissolved oxygen and removal of metabolic wastes (FAO, 2022). Unlike pond culture, cage farming utilizes existing water resources without extensive land modification. Fish remain protected within the enclosure while natural water circulation maintains suitable environmental conditions for growth. Cage culture can be practiced in freshwater reservoirs, lakes, rivers, irrigation canals, estuaries, and marine coastal waters depending on the cultured species and environmental conditions (Beveridge, 2004). The primary objective of cage culture is to maximize fish production by utilizing underexploited water bodies in an environmentally sustainable manner. Proper management of stocking density, feed, water quality, and fish health is essential to achieve high productivity and profitability.

Types of Cage Culture

Cage systems are classified according to their design, construction materials, and location within the water body.

Floating Cages

Floating cages are the most commonly used systems in reservoirs, lakes, and coastal waters. They consist of floating frames made from high-density polyethylene (HDPE), galvanized iron (GI), or PVC pipes, which support net enclosures suspended beneath the water surface. Floating cages automatically adjust to fluctuations in water level and are suitable for large-scale commercial fish farming (ICAR, 2023).

Fixed Cages

Fixed cages are anchored to the bottom of shallow water bodies using wooden poles, bamboo, or concrete supports. These cages remain stationary throughout the production cycle and are generally used in rivers, canals, and shallow lakes where water levels remain relatively stable.

Submersible Cages

Submersible cages are designed for offshore marine aquaculture where strong waves and storms are common. During adverse weather conditions, these cages can be lowered below the water surface, reducing structural damage and improving fish survival.

Site Selection for Cage Culture

Selection of a suitable site is one of the most critical factors determining the success of cage farming. An ideal site should provide adequate water depth, good water quality, sufficient water exchange, and protection from strong currents and pollution sources (FAO, 2022). Important criteria for site selection include:

- Water depth of at least 5–10 m below the cage bottom.
- Dissolved oxygen above 5 mg/L.
- Water temperature suitable for the cultured species.
- Moderate water current for continuous water exchange.
- Absence of industrial, agricultural, or domestic pollution.
- Accessibility for feeding, monitoring, and harvesting.
- Protection from floods, storms, and excessive wave action.

Environmental impact assessment should also be conducted before cage installation to minimize ecological disturbances and ensure responsible aquaculture practices.

Cage Design and Construction

The design of a fish cage significantly influences fish growth, survival, operational efficiency, and production costs. Modern cages are generally square, rectangular, or circular and are constructed using corrosion-resistant materials to ensure durability under aquatic conditions.

A typical cage system consists of:

- Floating frame (HDPE, PVC, or galvanized iron)
- Net enclosure (knotless nylon or HDPE net)
- Floats for buoyancy
- Sinkers or weights to maintain net shape
- Mooring and anchoring system
- Bird protection net
- Feeding platform and walkways (for large commercial farms)

The mesh size of the net should be selected according to the size of cultured fish to prevent escape while maintaining adequate water exchange. Regular inspection and maintenance of cage structures help prevent damage, predator attacks, and fish losses.

Suitable Fish Species for Cage Culture

Several freshwater and marine fish species are successfully cultured in cage systems depending on environmental conditions and market demand.

Common freshwater species include:

- Pangasius (*Pangasianodon hypophthalmus*)
- Tilapia (*Oreochromis niloticus*)
- Rohu (*Labeo rohita*)
- Catla (*Catla catla*)
- Common carp (*Cyprinus carpio*)
- Amur carp
- Jayanti rohu

Marine cage culture commonly includes:

- Asian seabass (*Lates calcarifer*)
- Cobia (*Rachycentron canadum*)
- Silver pompano (*Trachinotus blochii*)
- Groupers (*Epinephelus* spp.)
- Snappers (*Lutjanus* spp.)

Selection of species should depend on local environmental conditions, seed availability, market demand, growth rate, disease resistance, and farming objectives.

Feeding and Farm Management

Scientific feeding management is essential for achieving optimum growth and feed efficiency in cage culture. Commercial floating pellets containing balanced levels of protein, lipids, vitamins, and minerals are commonly used because they minimize feed wastage and facilitate observation of feeding behaviour (NRC, 2011). Feeding frequency depends on fish size, water temperature, and species. Farmers should avoid overfeeding because uneaten feed increases nutrient loading and deteriorates water quality. Regular monitoring of fish growth, feed conversion ratio (FCR), mortality, and water quality parameters such as dissolved oxygen, temperature, pH, ammonia, and transparency is necessary for efficient farm management. Routine health monitoring, net cleaning to remove biofouling organisms, predator control, and periodic grading of fish help improve

production efficiency and reduce disease incidence. Adoption of good aquaculture practices (GAqP) and biosecurity measures further enhances the sustainability and profitability of cage farming (FAO, 2024).

Advantages of Cage Culture

Cage culture has become one of the most promising aquaculture systems because it utilizes existing water resources efficiently while requiring relatively low land investment (Table 1). Compared with conventional pond farming, cage culture offers several technical, economic, and environmental advantages that make it an attractive option for fish farmers. The major advantages include:

- Efficient utilization of reservoirs, lakes, rivers, and other open water bodies.
- Lower land requirement and reduced pond construction costs.
- Continuous exchange of fresh water, resulting in better water quality.
- Higher stocking densities and increased fish production.
- Easy observation of fish feeding and health status.
- Simple harvesting and stock management.
- Better feed utilization and improved Feed Conversion Ratio (FCR).
- Lower labour requirement for routine management.
- Higher productivity per unit volume of water.
- Opportunities for livelihood generation and rural employment (FAO, 2022).

Because fish remain confined within cages, farmers can monitor growth, mortality, feeding behaviour, and disease symptoms more effectively than in many extensive culture systems. This improves farm management and enhances production efficiency.

Challenges and Limitations

Despite its numerous advantages, cage culture also faces several biological, environmental, and management-related challenges (Table 1). Overstocking, poor feed management, inadequate water exchange, and improper site selection may deteriorate water quality and increase disease outbreaks (Beveridge, 2004). Common constraints include:

- High initial investment for cage installation.
- Damage caused by storms, floods, or strong water currents.
- Net fouling due to algae, mussels, and other aquatic organisms.
- Escape of fish because of damaged nets.
- Disease outbreaks under high stocking densities.
- Water pollution resulting from excessive feed wastage.
- Predation by birds and aquatic animals.
- Conflicts with navigation, irrigation, or recreational activities.
- Limited availability of quality seed and formulated feed.

Regular cage maintenance, scientific stocking density, biosecurity measures, and continuous water quality monitoring are essential to minimize these challenges and ensure profitable production.

Table 1. Advantages and Challenges of Cage Culture

Aspect	Advantages	Challenges
Resource Utilization	Efficient use of reservoirs, lakes, rivers, and coastal waters	Site selection is critical for long-term sustainability
Infrastructure	Low land requirement and reduced pond construction costs	Initial investment for cage installation can be high

Aspect	Advantages	Challenges
Water Quality	Continuous water exchange maintains good environmental conditions	Water pollution may occur if feed is poorly managed
Fish Production	High stocking density and rapid growth	Overstocking may increase disease risk
Feeding	Better observation of feeding behaviour and reduced feed wastage	Dependence on high-quality commercial feed
Fish Health	Easy monitoring of fish behaviour and disease symptoms	Disease outbreaks can spread rapidly in intensive systems
Harvesting	Simple harvesting and stock management	Net damage may result in fish escape
Livelihood	High profitability and employment opportunities	Requires technical knowledge and regular maintenance

Economic Importance of Cage Culture

Cage culture has emerged as an economically viable aquaculture practice because it provides high production with comparatively lower infrastructure requirements. Farmers can establish cage farms in existing reservoirs or lakes without investing in pond excavation or land development, thereby reducing capital costs (ICAR, 2023). The system supports high stocking densities, rapid fish growth, efficient feed utilization, and shorter production cycles, leading to higher economic returns. Cage farming also creates employment opportunities in hatcheries, feed manufacturing, cage fabrication, fish transportation, processing, and marketing. Government initiatives such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and support from the National Fisheries Development Board (NFFDB) have further encouraged cage culture by providing financial assistance, technical guidance, and training programmes to fish farmers. These initiatives contribute significantly to rural livelihood improvement and entrepreneurship development in the fisheries sector.

Environmental Sustainability

When properly managed, cage culture can contribute to sustainable aquaculture by utilizing existing water bodies without altering natural landscapes. Efficient feed management, scientific stocking density, and regular environmental monitoring reduce nutrient loading and minimize ecological impacts (FAO, 2024). The adoption of environmentally responsible practices such as high-quality floating feeds, periodic cage cleaning, proper waste management, and responsible health management helps maintain water quality and aquatic biodiversity. Continuous monitoring of dissolved oxygen, ammonia, temperature, and other water quality parameters enables farmers to identify potential problems at an early stage and implement corrective measures. The integration of cage culture with modern technologies such as automated feeders, water quality sensors, artificial intelligence (AI), and Internet of Things (IoT)-based monitoring systems is further improving environmental sustainability and production efficiency.

Future Prospects

The future of cage culture is closely linked with technological innovation, sustainable resource management, and digital aquaculture. Modern cage farming is gradually adopting precision aquaculture technologies, including automated feeding systems, remote water quality monitoring, AI-based fish health management, drones, and cloud-based farm management systems (FAO,

2024). Development of durable cage materials, improved fish genetics, nutritionally balanced feeds, and advanced disease surveillance systems will further increase productivity and profitability. Expansion of cage farming in reservoirs, hydropower dams, floodplain wetlands, and coastal waters offers tremendous opportunities to meet the increasing global demand for fish while conserving land and freshwater resources. With appropriate government policies, farmer training, financial support, and scientific management, cage culture is expected to become one of the most important aquaculture production systems for ensuring food security, employment generation, and sustainable fisheries development.

Conclusion

Cage culture has emerged as a profitable, resource-efficient, and environmentally sustainable aquaculture practice capable of utilizing underexploited water resources for fish production. Compared with traditional pond farming, cage culture offers several advantages, including efficient water utilization, higher productivity, easy farm management, and lower land requirements. Successful cage farming depends on proper site selection, scientifically designed cages, quality seed, balanced nutrition, regular health monitoring, and adoption of good aquaculture practices. The integration of digital technologies, improved feeds, and modern management strategies is expected to further enhance the sustainability and profitability of cage culture. With increasing demand for aquatic food and growing pressure on land and freshwater resources, cage culture will continue to play a significant role in improving fish production, enhancing farmers' income, and supporting sustainable aquaculture development worldwide.

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HYDROPONICS UNVEILED: ADVANCED STRATEGIES FOR HIGH YIELD HORTICULTURAL CROPS

Amrutha P

Ph. D. Scholar, Department of Fruit science, University of Horticultural Sciences,
Bagalkot, College of Horticulture, Bangalore- 560065, Karnataka
Corresponding Email: amruthap3@gmail.com

The current horticultural landscape emphasizes maximizing production and productivity to meet the food demands of an ever-growing population. However, the land available for horticultural cultivation is steadily diminishing due to rapid industrialization and urbanization. This raises a critical question: how can we produce more crops within a smaller land area?

One promising solution is hydroponics, a soil-less cultivation technique that eliminates the need for traditional soil while providing plants with essential support, nutrients, and water through engineered systems. In conventional agriculture, soil serves as a medium for anchorage, nutrient storage, and water retention. Hydroponics replaces this natural function with controlled delivery of mineral nutrient solutions, ensuring optimal conditions for plant growth and development.

Globally, the adoption of hydroponics reflects its advantages in resource efficiency and adaptability. By precisely managing root-zone chemistry (pH, electrical conductivity, dissolved oxygen) and microclimate factors (vapor pressure deficit, CO₂ concentration, light intensity), hydroponics enables high-density, year-round production. Recent studies confirm significant improvements in yield, quality, and resource utilization, particularly when integrated with IoT-based automation, AI-driven monitoring, vertical farming systems, and stringent sanitation protocols.

What is Hydroponics?

The term *Hydroponics* originates from the Greek words *hydro* (water) and *ponos* (labor). It refers to a soil-less cultivation method where plants grow using mineral nutrient solutions instead of soil. Terrestrial plants can be grown with their roots immersed directly in nutrient solutions or supported by inert substrates such as perlite, gravel, or mineral wool (Verma *et al.*, 2024; Choorappulakkal *et al.*, 2024). Hydroponics enables precise control over nutrient delivery, water availability, and root-zone conditions, making it a cornerstone of modern controlled environment agriculture (CEA).

How Does a Hydroponic System Work?

In traditional agriculture, soil acts as a reservoir for water and nutrients and provides mechanical support. Hydroponics eliminates soil, requiring external structures for plant support and engineered systems for nutrient and water supply. These systems maintain optimal pH, electrical conductivity (EC), dissolved oxygen (DO), and temperature to ensure efficient uptake and growth (Dennison *et al.*, 2025; Adarsha *et al.*, 2025).

Advanced Hydroponic Techniques

Recent literature categorizes hydroponic systems into several advanced types, each with unique design and control parameters (Sowmya *et al.*, 2024; Qureshi *et al.*, 2025)

1. **Solution Culture:** Plants are supported externally with roots submerged in a nutrient solution. No solid media is used. Controls include pH (5.5-6.5), EC (1.2-2.0 mS/cm), and DO (>6 mg/L).
2. **Medium Culture:** Plants grow in inert substrates (rockwool, sand, gravel) enriched with nutrient solution. EC (1.5-2.2 mS/cm) and substrate moisture (60-80%) are critical.
3. **Aeroponics:** Roots are suspended in air and misted with nutrient solution droplets (50-120 μ m). Duty cycles (2-5 s ON / 3-8 min OFF) and VPD (0.6-1.2 kPa) are key for high oxygenation and rapid growth.
4. **Nutrient Film Technique (NFT):** A thin film of nutrient solution flows through sloped channels (1-3%) past bare roots. Flow rate (1-2 L/min/channel) and DO (>6 mg/L) must be maintained.
5. **Deep Flow Technique (DFT):** Similar to NFT but with deeper channels, providing buffering against flow interruptions.
6. **Deep Water Culture (DWC):** Roots are submerged in aerated reservoirs. Airflow (0.5-1.0 L/min/plant) and DO (7-8 mg/L) are essential for fruiting crops like tomato and cucumber.

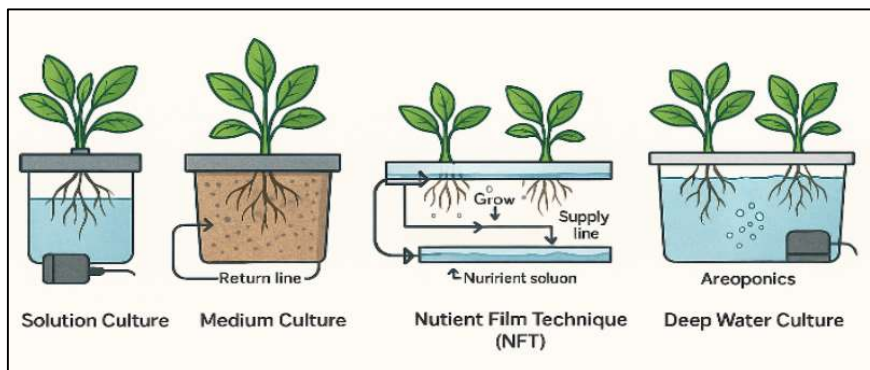


Fig 1: Types of Hydroponic Systems: Structural Layout and Root-Zone Configuration

Recent Insights and Applications

Modern hydroponic systems increasingly integrate IoT sensors, AI-driven nutrient optimization, and vertical farming designs to enhance yield and resource efficiency (Choorappulakkal *et al.*, 2024; Dennison *et al.*, 2025; Sowmya *et al.*, 2024). These innovations enable real-time monitoring of pH, EC, temperature, and CO₂, automated dosing, and predictive analytics for crop scheduling.

Crops That Can Be Grown in Hydroponics

Hydroponics supports a wide range of horticultural crops, including leafy greens (lettuce, spinach), herbs (basil, coriander, mint, oregano, parsley), fruiting vegetables (tomato, cucumber, capsicum), root crops (beet, radish), and small fruits (strawberry). Ornamental plants and flowers such as lavender and fennel are also successfully cultivated in controlled hydroponic systems (Verma *et al.*, 2024; Sowmya *et al.*, 2024).

Advantages of Hydroponics

There are many advantages of growing plants under soil-less culture over soil-based culture.

- **Higher yield and faster growth** due to direct nutrient delivery and optimized root-zone conditions (Thapa *et al.*, 2024).
- **Space and water efficiency**, requiring only ~20% of water and ~20% of land compared to traditional farming (Choorappulakkal *et al.*, 2024).

- **Reduced pest and disease pressure**, eliminating soil-borne pathogens and weeds (Dennison *et al.*, 2025).
- **Consistent quality and year-round production**, especially in controlled environments (Qureshi *et al.*, 2025).

Limitations of Soil-less Culture

Despite its benefits, hydroponics faces challenges:

- **High initial investment** and energy requirements for pumps, aeration, and climate control (Malabadi *et al.*, 2024).
- **Technical expertise** for nutrient management and system maintenance (Adarsha *et al.*, 2025).
- **Risk of system failure**, requiring redundancy and monitoring (Garzón *et al.*, 2023)

Future Scope of Hydroponics Technology

Hydroponics is increasingly viewed as a climate-smart solution for food security in water-limited regions. Studies predict cost reductions through automation, AI-driven nutrient optimization, and IoT-based monitoring, making hydroponics feasible for developing countries. Successful implementations in arid regions like Israel demonstrate its scalability: containerized hydroponic farms producing berries and citrus under fully automated systems have achieved yields far exceeding conventional soil farming.

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INNOVATIVE ENGINEERING SOLUTIONS FOR MODERN AQUACULTURE

Guguloth Harikrishna

Kerala University of Fisheries and Ocean Studies (KUFOS) Kerala – 682506

Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Aquaculture is considered a sustainable alternative to capture fisheries by improving resource utilization, reducing environmental impacts, and increasing production efficiency. To address challenges related to feed management, pollution control, and sustainable production, advanced technologies are being introduced, leading to the development of precision aquaculture. Precision aquaculture is a management approach based on continuous observation, measurement, and response to spatial and temporal variations in aquaculture systems. It applies control and engineering principles to improve farm monitoring, decision-making, and management of biological processes. This review provides an overview of recent technological innovations in precision aquaculture, including computer vision systems for fish monitoring, environmental monitoring tools, sensor networks, robotics, and data-based decision support systems. Technologies such as the Internet of Things (IoT), wireless sensor networks, and artificial intelligence enable real-time data collection, analysis, and communication between farming systems and users. These advanced tools help improve production efficiency, maintain water quality, enhance fish welfare, and ensure better quality of aquaculture products.

Introduction

Aquaculture provides a significant share of total fisheries production through land-based ponds and water-based systems such as pens, cages, longlines, and stakes in brackish water and marine habitats. It is considered a sustainable alternative to wild fish consumption by reducing inputs, optimizing outputs, and reducing pollution. However, aquaculture still faces several environmental impacts, including habitat destruction, the use of wild fish for feed production, and water pollution. To minimize these impacts, different technologies have been developed, giving rise to the concept of precision aquaculture. Precision aquaculture is a management approach based on observing, measuring, and responding to spatial and temporal variability in production systems. It applies control-engineering principles, modern sensor technologies, statistical analysis, and artificial intelligence to improve the monitoring, control, and documentation of biological processes in fish farms. Digital applications, remote observation, automatic monitoring technologies, computer image analysis, robotics, and Internet of Things (IoT) technologies provide accurate information related to fish growth, behavior, health, feeding, and water quality (Antonucci *et al.*, 2020). These technologies support data collection, real-time monitoring, intelligent control, and decision-making, helping to improve productivity and environmental sustainability in aquaculture systems.

Computer Vision for Animal Monitoring

Computer vision technologies are increasingly used in aquaculture for monitoring and managing fish populations through applications such as counting, size measurement, weight estimation, species identification, sex detection, health assessment, and behavior monitoring. These

technologies provide a non-invasive approach for observing fish in cages, ponds, tanks, and natural environments. However, their application is challenging because fish are sensitive, continuously moving organisms, and underwater conditions such as light availability, visibility, and environmental stability are difficult to control. Different imaging systems, including surface cameras, underwater stereo cameras, acoustic cameras, sonar systems, and LiDAR, are used to collect real-time information on fish characteristics and activities (Cui *et al.*, 2025).

Computer vision helps farmers in accurate counting of eggs, larvae, fry, and adult fish, improving stocking management, feeding strategies, and production planning. Stereo vision systems allow estimation of fish size and weight without handling, reducing stress and improving accuracy. These systems have also been applied for monitoring fish growth, swimming behavior, feeding activity, stress responses, and welfare conditions. In addition, image analysis and artificial intelligence-based methods enable automatic tracking and identification of fish, providing valuable information for farm management. Overall, computer vision technology supports precision aquaculture by improving animal monitoring, reducing human errors, optimizing resource use, and promoting sustainable fish production. However, further improvements are required to overcome challenges related to water turbidity, lighting variations, fish movement, and monitoring conditions.

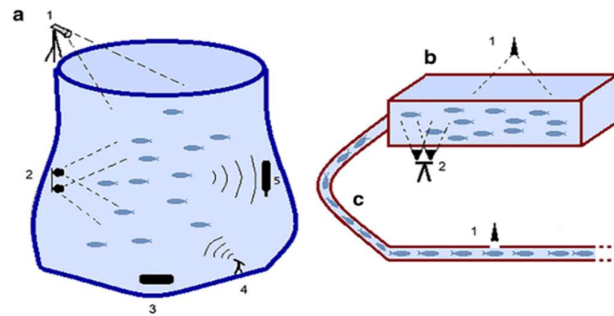


Fig. 1 Computer vision system for aquaculture

Environmental Monitoring Tools and Sensor Networks

Environmental monitoring tools and sensor networks play an important role in precision aquaculture by providing continuous information about water quality and farming conditions. In intensive aquaculture systems, maintaining suitable environmental conditions is essential for fish growth, survival, and overall production performance. With advancements in integrated microcomputers such as Arduino and Raspberry Pi, sensor-based monitoring systems have become more accessible for aquaculture applications. Water quality parameters including temperature, dissolved oxygen, pH, ammonia, nitrate, salinity, and alkalinity can be continuously monitored using sensors, and the collected data can be transmitted to farmers through cloud-based systems for better decision-making. These parameters directly influence fish health, feed utilization, growth rate, and carrying capacity of aquaculture systems. Wireless Sensor Networks (WSN) enable real-time monitoring by collecting environmental information from culture systems, although their application in underwater environments is challenging due to harsh conditions, sensor cost, and energy requirements. Advanced communication technologies such as ZigBee and Long-Range Wide Area Network (LoRaWAN) have improved wireless data transmission and monitoring efficiency in aquaculture systems. Smart sensor systems can provide real-time information on water quality parameters and help farmers take timely management decisions. Commercial solutions using imaging devices, cloud data storage, and underwater wireless sensors are also being developed for monitoring aquatic organisms and environmental conditions (Wang *et al.*, 2021). These sensor-based technologies improve farm management, reduce labor requirements, and support sustainable precision aquaculture by enabling accurate and continuous monitoring of culture environments.

Robotics

Robotics technology has emerged as an important innovation in precision aquaculture, particularly for improving feeding management and reducing labor requirements. Feeding is one of the major operational activities in aquaculture, and improper feeding can lead to feed wastage, accumulation of organic matter, and deterioration of water quality. The application of robotic systems helps to optimize feeding accuracy, reduce feed loss, and improve farm productivity. Automated feeding systems, including drone-based technologies and robotic feeders, can distribute feed uniformly in cages and ponds, ensuring that aquatic animals receive appropriate amounts of feed. These systems can also be adapted for delivering other farm inputs such as medicines, vaccines, and fertilizers. Robotic systems developed for aquaculture can perform tasks such as automatic feeding, water quality monitoring, and farm management through remote control and internet-based platforms. These systems are equipped with sensors to measure important water parameters and provide real-time data for better decision-making (Forhad *et al.*, 2024). Commercial robotic feeding systems have also been developed to improve feed efficiency and reduce labor costs by managing feeding operations in multiple tanks. Robotics provides an effective approach for precise feeding, reducing environmental impacts, minimizing waste, and enhancing the efficiency and sustainability of modern aquaculture systems.

Data Interpretation and Decision Tools

Data interpretation and decision-support tools are important components of precision aquaculture, helping farmers to analyze information and make accurate management decisions. Aquaculture systems involve complex factors related to environmental conditions, biological processes, and production management, which require effective data analysis and decision-making approaches. Decision Support Systems (DSS) integrate hardware and software technologies to collect, process, and analyze physicochemical and biological data for improving farm operations. The integration of IoT, wireless sensor networks, and analytical algorithms enables real-time monitoring and interpretation of aquaculture data. Advanced systems using wireless sensor nodes and high-precision sensors can collect environmental information, monitor water quality parameters, and improve the accuracy of farm management decisions. IoT-based DSS can help prevent potential risks by continuously monitoring environmental conditions and optimizing resource utilization in aquaculture facilities. Mathematical models and control algorithms are also used to improve production efficiency and optimize farming practices. Commercial precision aquaculture systems use sensing technologies, data analysis, and automated control methods to improve fish health monitoring, reduce losses, enhance production efficiency, and minimize environmental impacts (Ranjan *et al.*, 2026). These data-driven decision tools play a significant role in the development of modern and sustainable aquaculture.

Term Map Analysis

Term map analysis is a bibliometric approach used to understand research trends, relationships, and development patterns in precision aquaculture. In this study, international research articles published between 1991 and 2019 were analyzed using literature review analytics, bibliometric methods, and network visualization tools. The Scopus database was used to collect research records related to aquaculture, and the software VOSviewer was applied to create and analyze bibliometric maps based on the identified publications. A total of 43,716 aquaculture-related publications were recorded during the study period, while 185 publications were specifically related to precision aquaculture technologies, including IoT, ICT, computer vision, and robotics.

The analysis showed a rapid increase in precision aquaculture research after 2016, indicating growing interest in digital technologies for aquaculture development. The highest number of publications came from the European Union, China, India, the USA, and South Korea. The term clustering analysis identified three major research areas: fish behavior monitoring using technologies such as computer vision, image processing, robotics, and automation; environmental monitoring based on sensors, IoT, water quality parameters, and real-time data collection; and aquaculture management involving algorithms, identification, production, and operational systems. The term mapping analysis also showed a shift in research focus from traditional studies on fish behavior, stress, and identification toward advanced technologies such as IoT, sensors, cloud computing, algorithms, and digital platforms (Solomon *et al.*, 2025). These findings indicate the increasing role of smart technologies in improving monitoring, management, and sustainability of modern aquaculture systems.

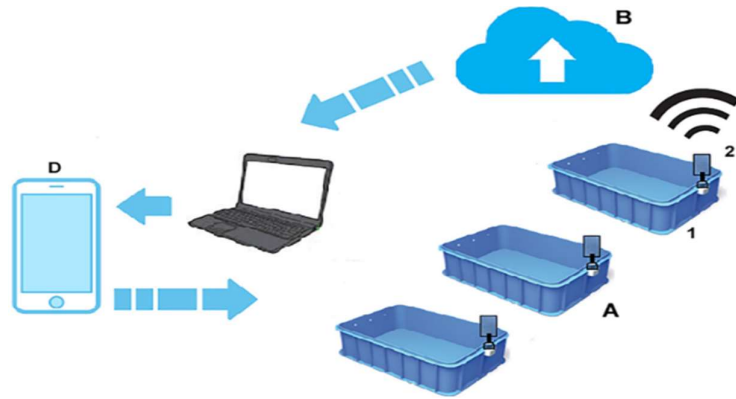


Fig. 2. A precision aquaculture information flow. Data acquired from sensors.

Conclusions

Precision aquaculture represents an important advancement in modern fish farming by integrating Industry 4.0 technologies, including cyber-physical systems, Internet of Things (IoT), Information and Communication Technologies (ICT), sensors, cloud computing, and Decision Support Systems (DSS). These technologies enable real-time monitoring, data analysis, and automated decision-making, helping to improve production efficiency, fish welfare, and product quality. The future of aquaculture requires a shift from experience-based management toward knowledge-driven approaches to achieve smarter and more sustainable production systems. In precision aquaculture, data collected from sensors installed in farming units can be transmitted through Wireless Sensor Networks (WSN) to cloud platforms, analyzed by DSS, and delivered to farmers through digital devices for effective management decisions. Although several technologies, such as acoustic and optical sensing systems for feeding control and size estimation, are already commercially available, other advanced systems, including underwater wireless sensors and cloud-based monitoring tools, still require further development and cost reduction for large-scale application. The continued progress of related fields such as precision agriculture and precision livestock farming will further support the implementation of precision aquaculture technologies and contribute to sustainable, efficient, and intelligent aquaculture production.

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**BREAKING DEPENDENCE: INDIA'S FERTILIZER VULNERABILITY
AND THE CASE FOR REGENERATIVE AGRICULTURE ALIGNED
WITH SDG 2, 12, 13 AND MISSION LIFE FOR VIKSIT BHARAT 2047****Abhay Singh^{1*}, Amandeep Singh² and Sanjeet Kumar Singh³**¹M.Sc. Scholar, Department of Agricultural Extension Education,
ANDUAT, Kumarganj, Ayodhya, Uttar Pradesh, India – 224229²M.Sc. Scholar, Department of Soil Science ANDUAT, Kumarganj,
Ayodhya, Uttar Pradesh, India, 224229³Assistant Professor, Department of Entomology,
Shri Murli Manohar Town Post Graduate College, Ballia, Uttar Pradesh, India - 277001*Corresponding Email: abhay.onea111@gmail.com**Abstract**

Geopolitical tensions around the Strait of Hormuz exposed critical vulnerability in India's agricultural system: extreme import dependence for fertilizers. When phosphate supplies tightened, fertilizer costs surged beyond affordability for 160 million smallholder farmers. Rather than temporary disruption, this signals structural weakness demanding systemic transformation. This paper examines geopolitical-agricultural linkages and presents evidence-grounded strategies for transitioning toward regenerative agriculture aligned with SDG 2, 12, 13 and Mission LIFE. Through state-level analysis (Punjab ZBNF initiatives and Uttar Pradesh FPOs), we demonstrate feasible pathways to reduce synthetic fertilizer dependency 40-50% within five years while maintaining yield stability. Success requires deliberate policy incentives, explicit barrier acknowledgment (subsidy reduction resistance, yield risks, extension capacity gaps), and realistic implementation timelines. This work bridges geopolitical risk analysis and agricultural policy reform, addressing literature gaps while identifying both opportunities and implementation challenges for India's 2047 sustainable development vision.

Keywords: Fertilizer vulnerability; Geopolitical risk; Regenerative agriculture; SDGs; Implementation barriers; Farmer resilience.

Introduction: Structural Fragility in Agricultural Supply Chains

India feeds 18% of humanity through agricultural output from 2.4% of global arable land a paradoxical achievement resting on precarious foundations. With 160 million farming households and agriculture contributing 18% of GDP, the sector anchors rural livelihoods and national food security. Yet this productivity depends critically on imported fertilizers: approximately 35-40% of total consumption, with phosphate imports satisfying 60% of demand and potassium dependency exceeding 90%. This import reliance was manageable when supply chains remained stable. That assumption collapsed dramatically. Geopolitical tensions around the Strait of Hormuz through which 21% of global maritime trade passes—disrupted fertilizer supplies. Iran, historically exporting 3 million tonnes of phosphate annually (7-8% of global output), faced sanctions constraining exports. Global phosphate spot prices surged from \$250-280/tonne (2021) to \$650-720/tonne (2023); potassium exceeded \$1,000/tonne versus pre-crisis \$350-400. For India, this created fiscal and economic crisis. Government subsidy burden escalated from ₹80,000 crore to ₹95,000 crore annually, straining fiscal capacity. In Punjab producing 50% of national wheat and

rice fertilizer consumed 55% of production expenses by 2023 versus 35% two years prior. Uttar Pradesh farmers reduced nitrogen application 20-30% to manage costs, risking yield penalties. This crisis exposed not temporary supply disruption but structural vulnerability. It simultaneously presents opportunity for transformative change toward regenerative agriculture aligned with SDG targets and Mission LiFE philosophy.

Geopolitical Vulnerability and the Case for Demand-Side Transformation

Global fertilizer markets suffer from dangerous concentration. Approximately 40% of phosphate supplies originate from three sources: Morocco, China, and historically Iran. Domestic phosphate production (₹4,500-5,500/tonne) costs more than imports (₹2,800-3,200/tonne pre-crisis), making import dependence economically rational. However, this strategy overlooked geopolitical risk. When Iranian exports restricted, alternative sources faced limitations: Morocco's Atlantic supplies vulnerable to weather; Chinese supplies compete with rising Asian demand. The Hormuz disruption increased shipping insurance 300-400%, extended transit times 3-4 weeks, and pushed landed costs 30-40% higher. Government subsidy expansion provided short-term relief but generated moral hazard: farmers applied excess fertilizer assuming continued price protection, deepening long-term sustainability problems. Forward-looking risks intensify: climate change threatens North African phosphate deposits through water scarcity; geopolitical fragmentation will worsen. India cannot achieve supply-side food security through import substitution domestic production will never reach demand. The only sustainable solution demands demand-side transformation: consuming less synthetic nitrogen through biological fixation, optimizing nutrient use through precision agriculture, and rebuilding soil organic matter as nutrient reservoirs. This is pragmatic risk mitigation, not environmental romanticism.

SDG Alignment and Evidence from the Ground: Punjab and Uttar Pradesh

India's SDG commitments intersect directly with agricultural transformation. SDG 2 demands nutritional security through sustainable food systems yet Indian agriculture produces abundant calories while generating micronutrient deficiencies (52% women and 30% children anemic despite food availability). SDG 12 requires reducing chemical pollutant releases; Indian agriculture contaminates groundwater with nitrogen runoff (Punjab/Haryana aquifers exceed WHO safe nitrate limits) and pesticide residues. SDG 13 addresses agriculture's 13% contribution to national emissions. Mission LiFE reframes sustainability from constraint to livelihood opportunity. However, SDG language often obscures implementation realities. Meeting SDG 2 while accommodating growing food demand on diminishing land requires productivity increases. Viksit Bharat 2047 envisions developed India with rising consumption. Agriculture must simultaneously support development and remain sustainable. This tension demands pragmatic, sequenced solutions rather than rhetorical commitments.

Evidence from field experiences clarifies feasibility. Punjab's Zero Budget Natural Farming (ZBNF) program (since 2019) trained 5,000-7,000 farmers. Initial yield reductions of 15-25% occurred over two seasons, then gradually stabilized for those integrating complementary practices (crop residue management, mulching, legume intercropping). Critical insight: farmers abandoning ZBNF lacked premium markets; those capturing organic/low-chemical price premiums sustained engagement. Subsidy expansion alone failed economic incentives proved decisive. Uttar Pradesh's 850+ Farmer Producer Organizations (FPOs) achieved 30-40% cost reductions for bio-fertilizer bulk procurement. FPOs with embedded technical support maintained 75-85% member retention versus 35-40% without. Adoption patterns revealed: 15-20% were values-driven; 80-85%

pragmatically economics-driven. These lessons demonstrate that transformation is achievable but 'not automatic' conditional on price incentives, institutional support, and realistic timelines. Five-year targets for 40-50% dependency reduction are realistic only if policy reflects farm-level realities.

Strategic Pathways and Implementation Barriers

Four integrated strategies emerge from evidence: (1) Biological nutrient management—nitrogen-fixing bacteria, phosphate-solubilizing organisms, and mycorrhizal fungi satisfy 30-50% of nutrient demands; combined with precision agriculture (soil testing, GPS application), achieves 25-35% fertilizer reduction; (2) Legume integration pulses and oilseeds fix atmospheric nitrogen, reducing nitrogen requirements in subsequent crops 20-30 kg/hectare, improving soil health and farmer income through diversification; (3) Organic waste valorization composting units, vermicompost centers, and biogas facilities recover nutrients and energy while generating employment; (4) Farmer-producer organizations collective input procurement reduces costs 30-40%, improves bargaining power, and enables implementation at scale. Soil testing currently reaches <15% of farmers nationally, establishing baseline gaps for precision agriculture expansion.

Yet significant implementation barriers threaten scaling: (1) Fiscal constraints subsidy reduction faces political resistance while competing with other demands; (2) Yield risks transition periods threaten marginal farmer livelihoods and require income bridges and crop insurance; (3) Extension capacity gaps India maintains approximately 1 extension worker per 2,000 farmers with inadequate sustainable agriculture training; (4) Market infrastructure deficiency certification costs remain high, premium price markets are thin and concentrated in urban areas, and smallholder access is limited; (5) Structural constraints land fragmentation (average <1 hectare nationally) creates economies-of-scale challenges. Solutions exist for each barrier, but require integrated policy design and political commitment sustained across electoral cycles, currently uncommon in Indian governance.

Conclusion: Crisis as Inflection Point

The fertilizer crisis represents a genuine inflection point for Indian agriculture. Rather than treating this as temporary shock managed through subsidy expansion, enlightened policy should leverage crisis-induced flexibility for transformative change. Evidence from Punjab and Uttar Pradesh demonstrates that sustainable adoption accelerates when driven by economic incentives and institutional support, not moral appeals. Yield maintenance during transition remains non-negotiable. Transition subsidies and premium price assurance prove more effective than extension messaging alone. Transformation is achievable but requires specific conditions: sustained budget reallocation (25-30% of agricultural expenditure toward sustainable initiatives by 2030), genuine extension system strengthening, farmer participation in policy design, and realistic institutional development timelines. These preconditions are not assured.

Yet alternatives offer no respite. Continued import dependence amid intensifying geopolitical fragmentation exposes India to periodic crises and eroding farmer incomes. The choice between difficult reform now and crisis management repeatedly is not actually a choice but economic inevitability. The question is timing. Reducing synthetic fertilizer dependency 40-50% while maintaining productivity strengthens food security, improves soil health and micronutrient density, addresses malnutrition, reduces groundwater contamination, enhances farmer resilience against supply shocks, fulfills SDG commitments, and realizes Mission LiFE's vision of conscious

environmental stewardship integrated with livelihood security. Acting now, leveraging this moment of policy flexibility, offers the best prospect for transforming Indian agriculture toward sustainability, resilience, and genuine prosperity for farming communities across the journey toward Viksit Bharat 2047.

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INTEGRATED MANAGEMENT STRATEGIES FOR COTTON LEAFHOPPER (*Amrasca biguttula biguttula*) IN THE NORTH COTTON-GROWING ZONE OF INDIA

Satpal Singh^{1*}, Rishi Kumar¹, Amarpreet Singh¹, Subhash Chandra¹,
S. K. Sain¹, Rajesh³, S. K. Verma¹ and V. N. Waghmare²

¹ICAR-Central Institute for Cotton Research, Regional Station, Sirsa (Haryana), India

²ICAR-Central Institute for Cotton Research, Nagpur (Maharashtra), India

³College of Agriculture, Fatehpur, SKNAU, Jobner, (Rajasthan), India

*Corresponding Email: satpalsngh070@gmail.com

Abstract

Cotton is a major cash crop in *Kharif* season in the northern cotton growing zone of India for its high economic importance. In general, worldwide cotton is known as “White Gold”. After introduction and adoption of bollworm resistant Bollgard-I & Bollgard-II cotton by farmers, the maximum area(>90%) of American Cotton (*Gossypium hirsutum*) was sown with *Bt* cotton hybrids replacing non-*Bt* cotton hybrids in all three cotton growing zone of India. The American Cotton (*Gossypium hirsutum*) is more prone to sucking pest attack as compared to *Desi Cotton* (*Gossypium arboreum*). Among the sucking pest of cotton, whitefly, leafhopper and thrips are major pest in north cotton growing zone. During *Kharif* 2025-26 season, a severe outbreak of leafhopper was occurred in north zone. In North zone, during 2025-26 kharif season the total area of cotton was 11.78 lakh hectares and provisional cotton production was 32.34 lakh bales with 467 kg lint productivity per hectare in entire zone (CCI, India). The cotton yield was decreased due to early attack and prolonged population of leafhopper which prevailed above ETL along with other several biotic and a biotic factors i.e. heavy rains, bollworms attacks, diseases etc. Surprisingly, leafhopper emerged as serious concern among all sucking pest during 2025-26 season due to favourable climatic conditions. Therefore, information about lifecycle, alternate host, survival host during off-season, favourable climatic conditions and integrated management strategies should be elaborated and reach to each and every farmers to control the leafhopper population and increase the yield accordingly.

Introduction

Cotton is attacked by vast array of insect pests. In India, Cotton is attacked by 251 insect species out of 1326 species. After the introduction of bollworm resistant transgenic cotton, sucking pests acquired the status of major and yield limiting factor. After 2018, pink bollworm (PBW) acquired resistant and established in North zone and thereafter combination of PBW as well as either of sucking pests are a serious concern (Rishi Kumar et al. 2024). Among the sucking pest, Cotton jassid (*Amrasca biguttula biguttula* Ishida) (Hemiptera:Cicadellidae) a small, wedge-shaped, pale-green insect with two black spots on its fore wings is a pest of polyphagous in nature. The pest causes yield losses by sucking sap from cotton plants. Both nymphs and adults are damaging and feed through its piercing and sucking type mouth parts on underside of the leaves. Both the nymphs and adults inject toxic saliva in leaf tissue and cause yellowing of the leaves followed by browning and downward curling from leaf margins and finally cause hopper burns.

Nature of Damage & Symptoms:

- Sap sucking by nymphs & adults result in various levels of injury grades (I-IV) (Fig.-A).
- The initial symptom of leafhopper damage is marginal yellowing of leaves, followed by crinkling and curling of leaves across the plant.
- Under severe infestation, nymphs and adults suck cell sap and inject toxic saliva, leading to leaf drying, reduced photosynthetic activity, and the characteristic “hopper burn” symptom.

Figure A: Different Grades of Leafhopper Infestations:

Grade-I	Entire foliage is free from crinkling or curling with no yellowing with scattered presence of leafhopper in plant foliage	
Grade-II	Crinkling and curling of a few leaves in the lower portion of plant + marginal yellowing of leaves.	
Grade-III	Crinkling and curling of leaves almost all over the plant. Plant growth hampered	
Grade-IV	Extreme curling, crinkling, yellowing, bronzing and drying of leaves (Hopper Burn)	

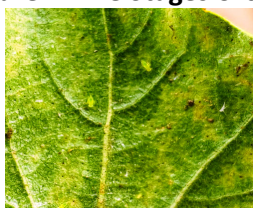
Hopper Burn: Hopper burn is an extreme damage symptom. In case of hopper burn, the whole plants leaf shows yellowing, burning, crumbly leaves and stunted growth. This damage causes the premature dropping of buds, square, flowers and bolls which resulting in significant yield losses to crop.

Activity period & Climate: The pest appeared in crop from 22nd-23rd SMW onwards and favoured by moderate temperature, humidity to attain its peak. In North zone peak activity of jassids was generally observed between 28-30th SMW. In 2025, jassids infestation started in 22nd Standard Meteorological Week (SMW) (28 May-02 June) and crossed ETL in 24th SMW (10 nymphs/3leaves) in cotton (Rishi Kumar *et al*, 2025). The population reached 18.93 nymphs/3leaves in July- August month in Haryana which was 3 times higher than ETL (6 nymphs/3leaves) (Rishi Kumar *et al*, 2025). The more rainy days (>14), moderate temperature and excessive rainfall (>350 mm) are favourable for early build-up of jassids population during June & July month in North Zone. In this context, if number rainy days remain same with approximate rainfall, then it's become again a serious pest during the current season.

Identification & Life Cycle: The eggs of jassids are curved and elongated in shape. Colour of eggs is yellowish white. The newly hatched first instars nymphs are transparent and greenish yellow in colour. The 2nd and 3rd instar nymphs are similar in shape and morphologically but in 3rd instar, wing pads developed prominently on the pterothorax. In 4th instar nymphs body is dark yellowish green colour and developed wing pads up to middle of abdomen. The adult is greenish in colour and very active flyer and able to jump and move here and there. The two black spots on forewings are prominent identification mark of the adult jassids.

Life Cycle: Jassids have incomplete metamorphism type life cycle. It means jassid complete life cycle in three stages i.e. eggs, nymph & adult instead of complete metamorphosis going through four life stages i.e. eggs, nymphs/larva, pupa & adult (Figure-B). Female of jassid laid 15 to 60 eggs individually into the soft tissue and midribs of large veins on the underside of cotton leaves. The eggs are not visible to the naked eye. The total eggs stage duration is 03-11 days. After completing the eggs period nymphs emerged from eggs. The total nymphal period is 5-16 days. Total average adult stage duration is ranged between 4-25 days. Overall life cycle of jassid is completed within 15-37 days based on biotic and abiotic factor (Nagrare et al. 2012).

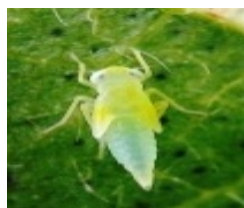
Figure B: Life Stages of Jassids



Eggs (Laid in veins not visible by naked eyes)



1st Instar



3rd Instar



Adult

Host range: Jassids are polyphagous pest in nature and complete its life cycle on cotton, okra, castor, groundnut, pigeon pea, soybean, sorghum, maize, cowpea, etc.

Prominent off -season host: Castor, potato, tomato, radish, marigold, etc.

Methodology for monitoring to assess Economic Threshold Level (ETL): Farmers are advised to monitor their field at regularly at weekly intervals at 30 days after sowing (DAS). For monitoring of sucking pest incidence at farmers field level, it is advised to monitor randomly 20 plants/acre, avoiding boarder and plants under shade of trees. Observe 3 leaves from upper, middle & lower strata of each plant. If average 6 nymphs/3leaves or Grade-II injury (crinkling, curling and marginal yellowing) symptoms are observed than apply recommended management practices to control the pest population.

✓ **Integrated Management of Leafhopper in Cotton:**

(A) Cultural Control Practices:

1. Follow crop rotation to break the life cycle of insect-pests.
2. Maintain the field, field bunds, irrigation channel clean and weed-free, as the weeds compete with the cotton crop for nutrition and harbour sucking pests.
3. Destroy volunteer/ratoon/infected cotton plants and weed hosts on or near irrigation channel/canal/bunds and in fallow lands.
4. Ensure heavy pre-sowing irrigation to obtain good germination and early establishment of plants.
5. Grow only recommended tolerant varieties / hybrids of cotton for Zone.
6. Complete the sowing of American cotton up to 15th May in North Zone.
7. Avoid excessive use of nitrogenous fertilizers.
8. Grow two rows of sorghum or pearl-millet or maize as boarder around cotton fields.
9. Create ecological diversity by growing *Desi* cotton and other non-host crops between the cotton fields.

(B) Mechanical Controls:

1. Install low-cost Yellow Sticky Traps (YST) @ 40 per acre for monitoring and control of jassids from June onwards.

**(C) Biological Control:**

1. To maintain ecosystems in cotton; protect natural enemies like spiders, green lacewings (*Chrysoperla*), ladybird beetles, spiders and syrphid flies.



Lacewings (Adult)

Lacewings
(Larva)ladybird beetles
(Adult)

Spider

2. Conserve the egg parasitoids like *Gonatocerus spp.* and others wasps or flies in cotton field which are help to suppress the populations of pest (S Mohan et al.2014).
3. **Microbial Biopesticides:** Use entomopathogenic fungi such as *Beauveria bassiana* or *Metarhizium anisopliae* or *Lecanicillium lecanii* during periods of high humidity for eco-friendly population suppression.

(D) Bio-rational or Botanical approaches:

1. NSKE 5% + Neem oil 5 ml /litre +1.0gm laundry detergent powder/litre water or Neem oil-based insecticide (300 or 1500 ppm) @ 1.0 litre per acre is advised to spray by using 150 litre water per acre.
2. Use any other available plant extract like pongamia oil in early stage of cotton.

- (E) **Chemical Control:** Chemical control should be initiated as and when pest crossed Economic Threshold Level (ETL) i.e. 6 nymphs/3leaves or Grade-II injury as crinkling, curling and marginal yellowing. For effective control, use ecologically safer insecticides like Dinotefuran 20 SG @ 60 gm or Flonicamid 50 WG @80 gm or Thiamethoxam 25 WG @40 gm or Tolfenpyrad 15 EC @400 ml or Fenpyroximate 5 EC@300 ml per acre in 150 litre per acre. Don't repeat the same insecticide.

Precautions during spray:

- i) Use fix type solid hollow cone nozzle.
- ii) Proper coverage of plants with insecticides is essential.
- iii) Spray insecticide before 12 noon or in the evening.
- iv) Do not repeat the insecticides of same group in subsequent sprays.
- v) Repeat the spray immediately if it rains within 24 hours after spray.
- vi) Use protective aids while using insecticides.
- vii) During spray wear all protective clothes, shoes, mask, goggles and hand gloves.
- viii) Dispose the pesticide container in proper manner.
- ix) Do not through the container in open area or field.

Conclusion/Summary: Cotton production depend on crop response to biotic factors (insect pest & diseases), abiotic factors (erratic rainfall, sudden drought, fluctuating temperature and humidity). Adoption of Integrated Pest Management (IPM), Integrated Disease Management (IDM), Integrated Nutrient Management (INM) Operational factors like timely sowing, insect pest

monitoring mechanism & weed management can further help in tackling the yield limiting factors. Cotton crop is highly prone to sucking pest and bollworms attacks, since last 4-5 years sucking pests and pink bollworm (PBW) are the major yield limiting factors in BG-II American hybrid cotton. Cotton leafhopper, *Amrasca biguttula biguttula*, is long time associated with cotton crop in North zone but remain at moderate and easily manageable level. More recently the pest emerged as a major sucking pest in the North Cotton-Growing Zone of India especially during last season. The pest population crossed the economic threshold level (ETL) in early stage of crop i.e. 30-40 days after sowing due to favourable weather conditions like more number of rainy days, excessive rain fall and moderate temperature during vegetative growth stage of cotton crop. Keeping into consideration the above facts, in case, during coming season same weather conditions occurred then leafhopper may pose a serious threat to cotton and need to be effectively managed using Integrated Pest Management (IPM) approach involving timely sowing, regular monitoring, conservation of natural enemies, use of neem-based products, installation of yellow sticky traps, and need-based application of recommended safer insecticides. Adoption of these components can minimize crop losses and ensure sustainable cotton production.

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VALUE ADDITION IN FISH: ENHANCING QUALITY AND MARKET VALUE

Krupa Tandel^{1*}, D.V. Bhola² and Tandel Vanshita³

¹Department of Fish Processing Technology,
College of Fisheries Science, KU, Veraval – 362265

²Department of Aquaculture, College of Fisheries Science, KU, Himmatnagar

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Fish is an excellent source of high-quality protein, essential amino acids, omega-3 fatty acids, vitamins, and minerals, making it one of the most nutritious foods for human consumption. However, fresh fish is highly perishable due to its high moisture content, enzymatic activity, and microbial spoilage, leading to considerable post-harvest losses. Value addition has emerged as an effective strategy to improve fish quality, extend shelf life, diversify fish products, and increase market value. It involves converting raw fish into convenient, safe, and consumer-friendly products through scientific processing, preservation, packaging, and branding. Value-added fish products such as fish fillets, fish fingers, nuggets, pickles, smoked fish, dried fish, fish sausages, surimi products, and ready-to-cook (RTC) or ready-to-eat (RTE) foods have gained increasing popularity due to changing consumer preferences and growing demand for convenience foods. Modern processing technologies, hygienic handling, cold chain management, and quality assurance systems further enhance product safety and export competitiveness. This article highlights the concept of value addition, processing methods, quality management, packaging technologies, and the role of value-added fish products in improving farmers' income and strengthening the fisheries sector.

Keywords: Value Addition, Fish Processing, Fish Products, Quality Management, Ready-to-Eat, Ready-to-Cook, Fish Marketing, Aquaculture.

Introduction

The fisheries and aquaculture sector plays a vital role in ensuring food security, nutritional security, employment generation, and economic development worldwide. According to the Food and Agriculture Organization (FAO), aquaculture supplies more than half of the aquatic animals consumed globally, and the demand for fish continues to increase because of its high nutritional value and health benefits (FAO, 2024). Fish contains high-quality proteins, essential amino acids, polyunsaturated omega-3 fatty acids, vitamins A, D, and B-complex, and minerals such as calcium, phosphorus, iodine, selenium, and zinc, making it one of the healthiest animal-source foods (FAO, 2022). Despite these advantages, fish is highly perishable due to rapid microbial growth, enzymatic degradation, and lipid oxidation after harvest. Poor handling, inadequate cold storage, and inefficient transportation often result in significant post-harvest losses, reducing both product quality and farmers' income. Value addition has become an important strategy to address these challenges by converting raw fish into diversified, safe, and high-quality products with greater consumer appeal and longer shelf life. Scientific processing, attractive packaging, quality certification, branding, and efficient marketing increase the commercial value of fish products while minimizing wastage (ICAR, 2023). The increasing urban population, changing lifestyles, rising

disposable incomes, and growing demand for convenient foods have further accelerated the market for ready-to-cook and ready-to-eat fish products. Consequently, value addition has become an essential component of modern fisheries and aquaculture, contributing significantly to employment generation, export earnings, and sustainable fisheries development.

Concept of Value Addition in Fish

Value addition refers to the process of improving the quality, shelf life, appearance, convenience, nutritional value, and marketability of fish through scientific processing, preservation, packaging, branding, and product diversification. Instead of selling raw fish alone, value addition converts fish into products that meet changing consumer preferences and generate higher economic returns (FAO, 2022). Value addition can be achieved through several approaches, including:

- Cleaning, grading, and hygienic dressing.
- Filleting and deboning.
- Smoking, drying, salting, and fermentation.
- Preparation of ready-to-cook (RTC) and ready-to-eat (RTE) products.
- Production of surimi and restructured fish products.
- Vacuum packaging and modified atmosphere packaging (MAP).
- Cold chain management and frozen storage.
- Branding, quality certification, and attractive packaging.

These interventions increase consumer acceptance, reduce post-harvest losses, improve food safety, and expand domestic and international market opportunities.

Importance of Value Addition in Fisheries

Value addition has become one of the most effective approaches for increasing profitability throughout the fisheries value chain. Scientific processing enhances product quality while simultaneously reducing spoilage losses and improving market competitiveness (ICAR, 2023).

Major benefits of value addition include:

- Extension of shelf life through scientific preservation.
- Reduction of post-harvest losses.
- Improved food safety and product quality.
- Better utilization of low-value fish species and processing by-products.
- Diversification of fish products to meet consumer demand.
- Higher market price and increased farmer income.
- Generation of employment in processing, packaging, transportation, and marketing.
- Promotion of exports through internationally accepted quality standards.
- Improved nutritional security by providing convenient fish-based foods.

Value addition also supports sustainable fisheries by encouraging the complete utilization of harvested fish and reducing unnecessary wastage during processing and marketing.

Major Value-Added Fish Products

The development of innovative fish products has significantly expanded market opportunities for the fisheries sector. Depending on processing techniques and consumer demand, numerous value-added products are commercially produced.

Fish Fillets

Fish fillets are boneless portions of fish obtained after removal of scales, skin (optional), bones, and viscera. Fillets are convenient for consumers because they require minimal preparation before

cooking. Hygienically prepared chilled or frozen fillets have high export demand due to their superior quality, uniform appearance, and convenience (FAO, 2024).

Ready-to-Cook (RTC) Fish Products

Ready-to-cook products require minimal preparation before consumption and are becoming increasingly popular among urban consumers. Common RTC products include:

- Fish fingers
- Fish cutlets
- Fish nuggets
- Fish burgers
- Fish balls
- Fish kebabs
- Fish steaks
- Fish curry cuts

These products are generally coated, seasoned, vacuum-packed, and stored under refrigerated or frozen conditions to maintain freshness and quality.

Ready-to-Eat (RTE) Fish Products

Ready-to-eat fish products are completely processed and can be consumed without further cooking. These products are particularly suitable for modern consumers seeking convenience and quick meal options. Examples include:

- Smoked fish
- Fish pickle
- Fish curry in retort pouches
- Canned fish
- Fish spreads
- Fish soup
- Fish snacks

Advanced thermal processing, retort technology, and aseptic packaging improve product safety while extending shelf life.

Smoked Fish

Smoking is one of the oldest preservation methods used in fisheries. During smoking, fish is exposed to controlled wood smoke, which reduces moisture content and deposits antimicrobial compounds on the product surface. Smoking improves flavour, aroma, texture, colour, and shelf life while reducing microbial spoilage (Fellows, 2017). Depending on processing temperature, smoking is classified into:

- Cold smoking
- Hot smoking

Smoked fish products have considerable demand in both domestic and export markets because of their unique sensory characteristics.

Fish Pickle

Fish pickle is a popular value-added product prepared by cooking fish pieces with edible oil, vinegar, salt, spices, and preservatives under hygienic conditions. The acidic environment and spices inhibit microbial growth, thereby extending shelf life. Fish pickle is highly suitable for small-

scale entrepreneurs because it requires relatively simple processing equipment while providing excellent market returns.

Fish Sausages and Surimi Products

Mechanically separated fish meat can be converted into various processed products such as fish sausages, fish rolls, fish sticks, imitation crab meat, and surimi-based products. Surimi is a concentrated myofibrillar protein prepared by repeated washing of minced fish muscle to improve texture and gel-forming properties. Surimi-based products possess high nutritional value, attractive texture, and excellent consumer acceptance in domestic and international markets (Park & Lin, 2022).

Dried and Fermented Fish Products

Drying and fermentation are traditional preservation techniques widely practiced in many Asian countries. Controlled drying reduces moisture content and inhibits microbial growth, whereas fermentation enhances flavour, digestibility, and shelf stability through beneficial microbial activity. Modern solar dryers, mechanical dryers, and hygienic fermentation technologies have significantly improved the quality and safety of traditional dried fish products.

Processing and Quality Management

The quality of value-added fish products largely depends on proper handling immediately after harvest. Hygienic harvesting, rapid icing, chilled transportation, and maintenance of the cold chain minimize microbial contamination and preserve freshness (FAO, 2024). Fish processing units should follow Good Manufacturing Practices (GMP), Good Hygienic Practices (GHP), Hazard Analysis and Critical Control Point (HACCP) principles, and Standard Sanitation Operating Procedures (SSOP) to ensure food safety. Quality assessment should include sensory evaluation, microbial analysis, chemical quality indicators, and proper packaging before marketing. The adoption of scientific quality management systems not only improves consumer confidence but also enhances export competitiveness by meeting national and international food safety standards.

Packaging and Storage Technologies

Packaging plays a crucial role in maintaining the quality, safety, and shelf life of value-added fish products. Scientific packaging protects fish from microbial contamination, oxidation, moisture loss, and physical damage during transportation and storage. Attractive packaging also enhances product appearance, provides nutritional information, and improves consumer confidence (FAO, 2024). Several advanced packaging technologies are currently used in the fish processing industry:

Vacuum Packaging

Vacuum packaging removes air from the package before sealing, thereby reducing oxygen availability for spoilage microorganisms and minimizing lipid oxidation. This technology helps maintain freshness, texture, flavour, and nutritional quality while extending refrigerated shelf life (Fellows, 2017).

Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging replaces atmospheric air with a controlled mixture of gases such as carbon dioxide (CO₂), nitrogen (N₂), and oxygen (O₂). The modified gas composition suppresses microbial growth and delays spoilage, making MAP highly suitable for chilled fish fillets and ready-to-cook products (FAO, 2022).

Cold Chain Management

An uninterrupted cold chain is essential for preserving fish quality from harvest to the consumer. Proper icing, refrigerated transportation, frozen storage, and temperature-controlled distribution reduce microbial growth and maintain product safety. Continuous monitoring of storage temperature is particularly important for frozen fish products to prevent quality deterioration (ICAR, 2023).

Food Safety and Quality Standards

Food safety has become a major concern in the fisheries sector due to increasing consumer awareness and international trade requirements. Value-added fish products must comply with national and international quality standards to ensure consumer health and market acceptance. Fish processing units should implement:

- Good Manufacturing Practices (GMP)
- Good Hygienic Practices (GHP)
- Standard Sanitation Operating Procedures (SSOP)
- Hazard Analysis and Critical Control Point (HACCP)

In India, the Food Safety and Standards Authority of India (FSSAI) regulates food safety standards, while export-oriented processing units must also comply with guidelines prescribed by the Marine Products Export Development Authority (MPEDA) and the Export Inspection Council (EIC). International trade is largely governed by the Codex Alimentarius Commission, which establishes globally accepted food safety standards (Codex Alimentarius Commission, 2023). Routine quality evaluation should include sensory assessment, microbial analysis, chemical quality parameters, packaging integrity, and traceability systems to ensure product safety and consumer satisfaction.

Economic Importance and Market Opportunities

Value addition significantly enhances the economic value of fish by converting low-priced raw materials into premium-quality products. Processing, packaging, branding, and product diversification increase consumer acceptance and generate higher returns for fish farmers, processors, and entrepreneurs (FAO, 2024). The growing demand for convenience foods has created substantial market opportunities for ready-to-cook (RTC) and ready-to-eat (RTE) fish products. Supermarkets, restaurants, hotels, institutional catering services, and online food delivery platforms have become important distribution channels for value-added seafood products. In addition, export demand for fish fillets, shrimp products, smoked fish, surimi, canned seafood, and frozen fish products has expanded considerably. The fisheries processing sector also creates employment opportunities in processing, packaging, cold storage, transportation, quality control, and retail marketing, thereby contributing to rural development and economic growth (Table 1).

Table 1. Major Value-Added Fish Products and Their Benefits

Value-Added Product	Processing Method	Major Benefits
Fish Fillets	Filleting and deboning	Convenience, higher market value
Fish Fingers & Nuggets	Mincing, coating, freezing	Ready-to-cook, consumer-friendly
Fish Cutlets & Burgers	Mincing, seasoning, cooking	High consumer acceptance
Fish Pickle	Cooking with spices and vinegar	Extended shelf life and improved flavour

Value-Added Product	Processing Method	Major Benefits
Smoked Fish	Hot or cold smoking	Enhanced flavour and preservation
Dried Fish	Controlled drying	Long shelf life and reduced spoilage
Fish Sausages	Emulsion processing	Product diversification and value addition
Surimi Products	Washing and refining fish mince	High-quality processed seafood
Canned Fish	Thermal processing	Long shelf life and export potential
Ready-to-Eat Products	Retort processing and packaging	Convenience and higher commercial value

Challenges in Value Addition

Despite considerable progress, several constraints continue to limit the growth of value-added fish processing, particularly in developing countries. Major challenges include:

- Inadequate cold chain infrastructure.
- Limited access to modern processing technologies.
- High investment costs for processing equipment.
- Shortage of skilled manpower.
- Poor awareness regarding food safety standards.
- Inconsistent quality of raw fish.
- High transportation and storage costs.
- Limited branding and marketing strategies.
- Competition in domestic and international markets.

Addressing these challenges requires improved infrastructure, technical training, financial support, and stronger collaboration among research institutions, government agencies, and the private sector.

Future Prospects

The future of value addition in fisheries is closely associated with technological innovation, automation, and changing consumer preferences. Increasing demand for healthy, nutritious, minimally processed, and convenient seafood products is expected to drive further growth in the fish processing industry (FAO, 2024). Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), blockchain-based traceability systems, smart packaging, nanotechnology, and advanced freezing techniques are improving product quality, food safety, and supply chain management. Sustainable packaging materials, eco-friendly processing technologies, and efficient utilization of fish processing by-products are also gaining increasing importance. The development of functional seafood enriched with omega-3 fatty acids, collagen, bioactive peptides, and nutraceutical compounds presents new opportunities for the fisheries industry. Continued investment in research, entrepreneurship, and quality certification will further strengthen domestic and export markets.

Conclusion

Value addition has become an indispensable component of modern fisheries and aquaculture by enhancing product quality, extending shelf life, reducing post-harvest losses, and increasing market value. Scientific processing, hygienic handling, advanced packaging, cold chain management, and quality assurance systems ensure the production of safe, nutritious, and

consumer-friendly fish products. The growing popularity of ready-to-cook and ready-to-eat seafood products offers excellent opportunities for farmers, entrepreneurs, and the food processing industry. Adoption of internationally accepted food safety standards and innovative processing technologies will further improve export competitiveness and consumer confidence. By integrating scientific processing, sustainable resource utilization, and effective marketing strategies, value addition can significantly contribute to food security, employment generation, rural livelihoods, and the long-term development of the fisheries sector.

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LARGE EXPERIMENTS OF FOUR-LEVEL IN SMALL BLOCKS: A CASE STUDY IN ONION MANAGEMENT

**Vankudoth Kumar^{1,2*}, Sukanta Dash², Med Ram Verma²,
Anil Kumar³, Archana A^{1,2} and Sunil Kumar Yadav²**

¹The Graduate School, ICAR-IARI, New Delhi-110012

²ICAR-IASRI, Pusa, New Delhi-110012

³Krishi Bhavan, ICAR, New Delhi-110012

*Corresponding Email: kumarvankudoth51@gmail.com

A complete factorial experiment may include all required treatment combinations yet still produce imprecise results when field plots vary systematically in soil fertility, moisture, drainage or other environmental conditions. Confounded blocking addresses this problem by arranging treatments in relatively homogeneous blocks without eliminating any treatment combinations. This article presents a four-factor onion-management experiment in which cultivar, nitrogen dose, irrigation interval and plant spacing are each evaluated at four levels, resulting in ($4^4 = 256$) treatment combinations. Depending on the extent of field heterogeneity and the practical requirements of field operations, the treatments may be arranged in four blocks of 64 plots, 16 blocks of 16 plots or 64 blocks of four plots. Selected higher-order factorial contrasts are deliberately confounded with block effects, thereby improving the precision of important main effects and selected low-order interactions. An R-based example demonstrates how the confounded block layout can be generated and prepared for randomization.

Keywords: Four-level factorial; confounded blocking; onion management; R package.

Introduction

Field experiments are essential for identifying the best combinations of crop management practices, but reliable conclusions depend on both the treatment structure and the way treatments are arranged in the field. Agricultural fields are rarely uniform; differences in soil fertility, moisture, drainage, salinity and previous crop history can influence crop growth and may conceal the true effects of experimental treatments. Blocking is therefore used to group similar plots and improve the precision of treatment comparisons. Field experiments are essential for identifying the best combinations of crop-management practices, but reliable conclusions depend on both the treatment structure and the arrangement of treatments in the field. Factorial designs allow several factors and their interactions to be investigated simultaneously, while blocking improves experimental precision by controlling variation among experimental units (Box *et al.*, 2005). The combination of four factors, each at four levels, produces ($4^4=256$) treatment combinations. Experiments with such large run sizes require systematic design-construction procedures to maintain desirable statistical and distributional properties (Li and Qin, 2020).

In the present onion-management experiment, four factors—cultivar, nitrogen dose, irrigation interval and plant spacing—are each studied at four levels. Their combination produces ($4^4 = 256$) treatment combinations, making the experiment comprehensive but operationally large. A confounded factorial block design provides a practical method for arranging these treatments into smaller, more homogeneous blocks while retaining the complete factorial treatment structure. Selected higher-order effects of comparatively less importance are associated with block effects so

that the main effects and important interactions can be estimated with greater precision. This approach makes the experiment more manageable, statistically efficient and suitable for studying several onion-production practices simultaneously under variable field conditions.

Case study: Onion-management

Consider an onion study with four factors at four levels. The exact values must be adapted to local production systems, but the structure below shows how quantitative and categorical practices can be studied together.

The full set contains $4^4 = 256$ treatments. Rather than treating the field as one large undivided area, the researcher may choose a block size that matches the physical scale of heterogeneity and the capacity of field operations.

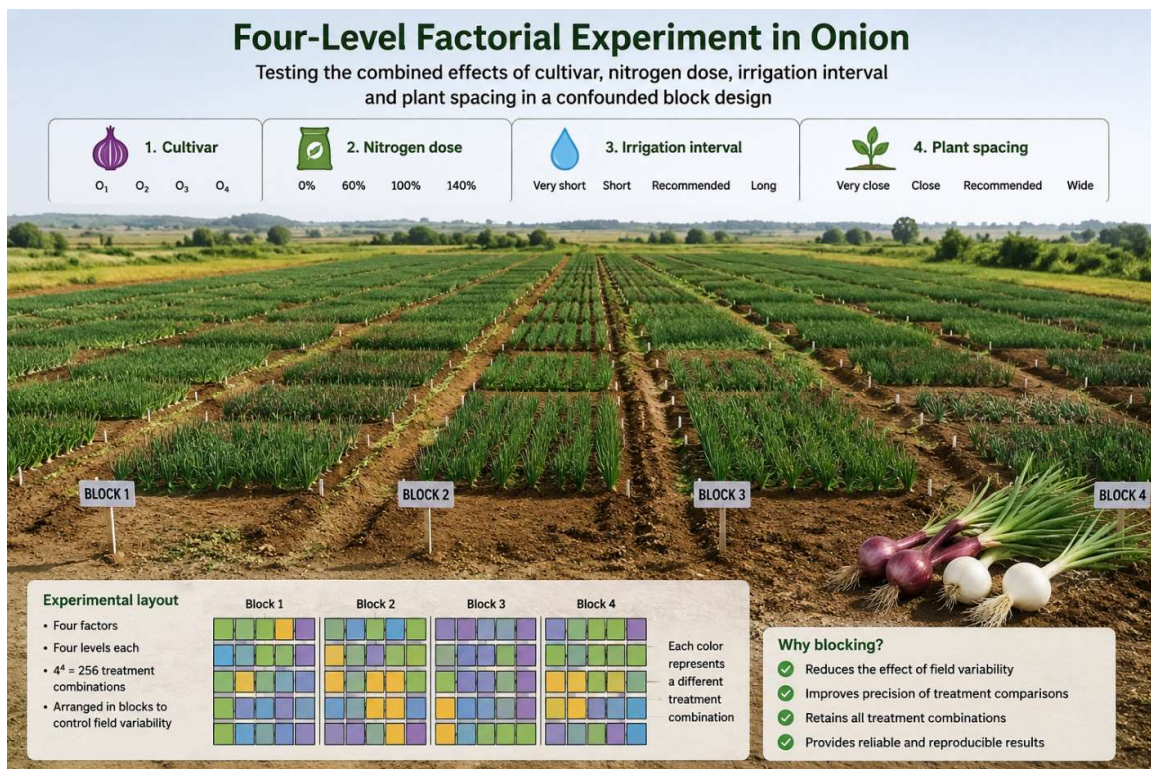


Figure 1. Blocking arrangement for a four-level field experiment

Generating the confounded design in R

Constructing a confounded factorial layout for four-level factors manually is difficult because all treatment combinations must be allocated systematically to blocks while selected factorial effects are deliberately confounded with block effects. The `lfebd3` package simplifies this task through the function `lfebd4.cf.full(n, r)`, where `n` specifies the number of four-level factors and `r` controls the block structure used in the construction (Kumar *et al.*, 2026). In the present example, `lfebd4.cf.full(n = 4, r = 1)` generates a complete confounded design for four factors at four levels, comprising $4^4 = 256$ treatment combinations. The generated object contains the treatment combinations organized according to the resulting block arrangement, and printing design displays the layout for inspection. This reproducible procedure reduces manual calculation and helps researchers verify the treatment-to-block allocation before preparing the final randomized field

plan. After generating the design, its structural and statistical properties may be further examined using the FactChar R package, which provides characterization and diagnostic tools for factorial block designs (Dash *et al.*, 2025). Such diagnostics can help researchers verify the properties of the design before implementing the final randomized field layout.

```
library(lfebd3)
design <- lfebd4.cf.full(n = 4, r = 1)
design
```

Conclusion

Confounded blocking provides a practical and statistically efficient approach for conducting a complete four-level factorial onion experiment under non-uniform field conditions. Using the R code, all $4^4 = 256$ treatment combinations can be generated and systematically allocated to blocks while preserving the complete factorial treatment structure. The gain in precision is achieved by confounding selected, comparatively less important factorial effects with block effects, thereby safeguarding the estimation of the main effects and interactions of primary scientific interest. Valid interpretation depends on the careful selection of confounded effects, an appropriate block size, proper randomization and complete documentation of the design. When these elements are planned together, the large factorial experiment becomes operationally feasible, statistically reliable and fully reproducible.

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HARNESSING BENEFICIAL RHIZOBACTERIA FOR SUSTAINABLE MANAGEMENT OF SEED ROT AND SEEDLING BLIGHT IN MAIZE

Anuradha Ojha^{1*} and Aakash Ojha²

¹PhD Scholar, Department of Microbiology,
Punjab Agricultural University, Ludhiana-141004, India.

²PhD Scholar, Department of Agronomy,
Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya,
Palampur- 176062, India

*Corresponding Email: anuradhaojha111@gmail.com

Abstract

Maize (*Zea mays* L.) is an important cereal crop contributing significantly to food, feed, and industrial sectors. However, diseases caused by *Fusarium verticillioides*, particularly seed rot and seedling blight, often reduce crop establishment and yield. Excessive dependence on chemical fungicides has raised concerns regarding environmental safety and soil health. Beneficial rhizobacteria, commonly known as Plant Growth-Promoting Rhizobacteria (PGPR), provide an eco-friendly alternative for disease management and crop improvement. Research conducted at Punjab Agricultural University identified two promising bacterial isolates, *Bacillus subtilis* and *Micrococcus luteus*, capable of suppressing *F. verticillioides* while enhancing maize growth. These bacteria produce antifungal metabolites, solubilize nutrients, synthesize plant growth-promoting substances, and stimulate the plant's natural defence mechanisms. Greenhouse and field evaluations demonstrated improved seed germination, reduced disease incidence, enhanced plant vigour, and increased grain yield following bacterial seed treatment. Adoption of such microbial technologies can reduce chemical pesticide use and contribute to sustainable maize production.

Keywords: Maize, PGPR, *Bacillus subtilis*, *Micrococcus luteus*, *Fusarium verticillioides*, biological control

Introduction

Maize is the third most important cereal crop after rice and wheat and serves as a staple food, livestock feed, and industrial raw material. Its cultivation has expanded rapidly because of its adaptability to diverse agro-climatic conditions and increasing demand from the poultry, starch, and biofuel industries. Despite its importance, maize productivity is frequently affected by several fungal diseases, among which seed rot and seedling blight caused by *Fusarium verticillioides* are particularly destructive. The pathogen infects seeds before and after germination, resulting in poor crop establishment, reduced plant vigour, and considerable yield losses.

Chemical fungicides are commonly used for disease management, but repeated applications increase production costs, leave chemical residues, and negatively affect beneficial soil microorganisms. Therefore, environmentally safe alternatives are becoming increasingly important. Beneficial rhizobacteria or PGPR have emerged as effective biological agents that not only suppress pathogens but also improve nutrient availability, stimulate plant growth, and enhance resistance against diseases. Recent research has demonstrated that microbial inoculants can become an integral component of sustainable maize production.

Importance of Beneficial Rhizobacteria

The rhizosphere is a biologically active zone surrounding plant roots where beneficial microorganisms interact closely with plants. Certain bacterial species colonize the root surface and promote crop growth through multiple mechanisms.

These beneficial bacteria:

- Protect roots from soil-borne pathogens.
- Improve phosphorus and micronutrient availability.
- Produce plant growth hormones such as indole-3-acetic acid (IAA).
- Produce siderophores that improve iron uptake.
- Enhance root growth and nutrient absorption.
- Stimulate the plant's natural defence system.
- Improve tolerance against environmental stresses.

These multiple functions make PGPR valuable biofertilizers as well as biological control agents.

Research Findings from Punjab Agricultural University

Extensive screening of maize rhizosphere bacteria identified two highly effective isolates, *Bacillus subtilis* and *Micrococcus luteus*, against *Fusarium verticillioides*. Laboratory studies showed that these bacteria significantly inhibited fungal growth through the production of diffusible and volatile antifungal metabolites.

Both isolates also possessed several plant growth-promoting characteristics including:

- Phosphate solubilization
- Siderophore production
- IAA production
- Biofilm formation
- Extracellular polysaccharide production
- Ammonia production

These properties enable the bacteria to establish themselves around maize roots while improving nutrient availability and suppressing pathogenic fungi.

Effect on Maize Growth

Seed treatment with the bacterial isolates produced encouraging results under greenhouse and field conditions.

The treated plants showed:

- Higher seed germination.
- Reduced seed rot and seedling blight.
- Increased root development.
- Improved plant height.
- Greater biomass accumulation.
- Enhanced grain yield.
- Better thousand-grain weight.

The combined application of *Bacillus subtilis* and *Micrococcus luteus* proved more effective than individual inoculation, indicating the advantage of using microbial consortia.

Natural Defence Activation

Apart from directly suppressing the pathogen, the bacterial isolates activated the maize defence system.

Higher levels of defence-related compounds such as:

- Phenolic compounds
- Peroxidase (PO)
- Phenylalanine ammonia-lyase (PAL)

were observed in treated plants. These enzymes strengthen plant tissues and reduce fungal colonization, thereby improving disease resistance.

Role of Microbial Metabolites

Advanced metabolite profiling using Liquid Chromatography-Mass Spectrometry (LC-MS) revealed that both bacterial isolates produce several antimicrobial and plant-beneficial metabolites. These naturally occurring compounds inhibit fungal growth, enhance plant metabolism, and improve stress tolerance.

The discovery of these metabolites supports the development of next-generation microbial bioformulations capable of replacing or reducing chemical fungicides in maize cultivation.

Benefits to Farmers

The adoption of microbial seed treatments offers several advantages:

- Reduced dependence on chemical fungicides.
- Lower production costs.
- Better seed germination.
- Healthy crop establishment.
- Improved nutrient use efficiency.
- Enhanced grain yield.
- Environmentally safe crop production.
- Improved soil microbial diversity.

Recommendations

Farmers should:

- Use certified healthy seed.
- Treat seed with recommended microbial bioformulations before sowing.
- Practice crop rotation.
- Maintain proper field sanitation.
- Apply balanced fertilizers and organic manures.
- Avoid indiscriminate fungicide application.
- Monitor crop health during early growth stages.

Conclusion

Beneficial rhizobacteria represent an effective and sustainable solution for managing seed rot and seedling blight of maize. Research conducted at Punjab Agricultural University demonstrated that *Bacillus subtilis* and *Micrococcus luteus* effectively suppress *Fusarium verticillioides* while promoting plant growth and improving grain yield. These microorganisms activate natural plant defence mechanisms and produce bioactive metabolites that contribute to disease suppression. Integration of microbial inoculants into maize production systems can reduce chemical inputs, improve soil health, and enhance long-term agricultural sustainability.

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FROM POND TO MARKET: TRANSFORMING WATER CHESTNUT MARKETING SYSTEMS

Aditya Kumar Maurya^{1*}, Deepa H. Dwivedi² and Shivangi Mishra¹

^{1,2}Research Scholar, Babasaheb Bhimrao Ambedkar University (Lucknow)

²Professor, Babasaheb Bhimrao Ambedkar University (Lucknow)

*Corresponding Email: adityamaurya3471@gmail.com

Water chestnut (*Trapa natans* var. *bispinosa*), a seasonal aquatic crop, holds significant nutritional and economic value, particularly in regions across Asia and parts of Europe. It is widely consumed fresh, dried, or processed into flour and snacks. Despite its demand, water chestnut remains an under-marketed crop with limited penetration into mainstream and international markets. Effective marketing strategies can help in maximizing returns for farmers, boost rural employment, promote sustainable agriculture, and introduce this nutritionally-rich food to global consumers. This article explores various marketing strategies for water chestnut, focusing on production, branding, market segmentation, digital outreach, and value addition.

Keywords - Water chestnut, market segmentation, branding

In many areas, farmers using pond-based cultivation systems rely heavily on water chestnut (*Trapa natans* var. *bispinosa*), a major aquatic horticulture crop. Water chestnut marketing is still mostly disorganized, ineffective, and controlled by conventional methods despite its nutritional worth, therapeutic qualities, and seasonal market need. Farmers frequently depend on local vendors or intermediaries, which limits price realization, causes losses after harvest, and lowers profitability. As a result, the water chestnut's journey from pond to market is characterized by a number of limitations, such as insufficient storage facilities, poor transportation infrastructure, lack of grading and standardization, and restricted access to valuable markets. The necessity of changing current marketing methods into more organized, transparent, and technologically advanced models has come to light more and more in recent years. Promising potential to improve efficiency and provide equitable rewards to producers are presented by the integration of contemporary supply chain management techniques, digital platforms, value addition, and cooperative marketing methods. Adoption of cold chain infrastructure, GIS technologies, and market intelligence systems can also greatly enhance market connections and lower post-harvest losses.



Market Dynamics and Target Segmentation

Understanding the Market :

Before developing any strategy, it's crucial to understand the existing market dynamics for water chestnuts:

- Geographic demand - Predominantly water chestnut is consumed in India, China, and Southeast Asia.
- Product forms - Water chestnut is generally consumed as fresh, boiled, canned, dried, or processed into flour.
- Seasonality - Typically water chestnut is harvested during late autumn, leading to a limited supply period.
- Customer base - Water chestnut includes rural and urban consumers, health-conscious buyers, and food processing industries.

Target Segmentation

Effective marketing requires targeting oriented segments:

- Local consumers - They emphasize on freshness, affordability and cultural significance.
- Urban and health-conscious consumers - Promote water chestnut as gluten-free, low-fat and nutrient-rich.
- Export markets - Focus more on Asian diaspora and specialty food markets in Europe and North America.
- Food processors and retailers - Encourage bulk buying through B2B partnerships.

Branding and Product Positioning

Brand Development

Branding water chestnut products can elevate their perceived value. Key branding elements include:

- Logo and packaging - Develop eco-friendly, attractive, and informative packaging.
- Taglines and messaging - Use terms like "Nature's Superfood," "Seasonal Wellness." or "Gluten-Free Power."
- Certification - Obtain organic or FSSAI/USDA certification to build consumer trust.

Product Positioning

Position water chestnut as:

- A seasonal delicacy with traditional and festive value.
- A super-food with high dietary fiber, potassium, and antioxidant content.
- A multi-purpose ingredient suitable for flours, snacks, sweets, and baked goods.

By redefining water chestnuts not just as a produce item but as a lifestyle food, producers can attract diverse consumer groups.

Value Addition and Product Diversification

Value addition increases marketability and profitability:

Processed Forms

- Water chestnut flour (Singhara atta): Popular during fasting seasons in India.
- Ready-to-eat snacks: chips, crisps, roasted kernels.
- Canned or vacuum-sealed products: For off-season consumption and export.

Packaging Innovations

- Use vacuum packs to extend shelf life.
- Introduce single-use packs for health-conscious individuals.
- Promote eco-friendly containers to appeal to sustainability-oriented consumers.

Distribution Channels

A multi-channel distribution strategy ensures maximum market reach:

Traditional Channels

- Local mandis and haats (markets).
- Wholesale markets via cooperatives or traders.

Modern Retail

- Tie-ups with supermarkets and organic food stores.
- Placement in farmers markets and health food outlets.

Online and Direct-to-Consumer (D2C) Channels

- Sell through e-commerce platforms like Amazon, Big Basket, and Flipkart.
- Create farm-to-door models via company websites or apps.
- Use subscription services for regular delivery of fresh or dried products.
- Use subscription services for regular delivery of fresh or dried products.

Promotional Strategies**Digital Marketing**

- Social media campaigns: Share recipes, health benefits, and harvesting stories of water chestnut on Instagram, YouTube, and Facebook.
- Influencer marketing: Collaborate with nutritionists, chefs, and food bloggers.
- Content marketing: Post blog articles, videos, and info-graphics about water chestnuts.

Offline Promotions

- Participation in food expos and agricultural fairs.
- Sampling campaigns in supermarkets and festivals.
- Educational seminars in schools, colleges, universities and community centers about nutritional benefits.

Seasonal Campaigns

- Launch festive-themed packaging during Diwali, Navaratri, or Thanks giving.
- Highlight its role in fasting and religious diets during specific months.
- Ensure phytosanitary certifications and packaging standards.
- Partner with export agencies and logistics firms for cold-chain management.

Pricing Strategy

- Pricing should reflect both the value addition and the target audience's capacity:
- Penetration pricing for rural or budget-conscious consumers.
- Premium pricing for health and organic product lines.
- Bulk pricing and discounts for B2B buyers or export markets.
- Providing combo offers, seasonal discounts, and subscription benefits can encourage repeat purchases.

Export Opportunities

With increasing demand for exotic and healthy foods globally, water chestnuts offer significant export potential:

Target Countries

United States, Canada, United Kingdom, Germany, Australia, New Zealand, Middle Eastern countries with large South-Asian populations.

Compliance and Logistics

Implementing these strategies can uplift farmer incomes, reduce post-harvest losses, and bring water chestnuts the recognition they deserve in the global food economy.

Collaborations and Partnerships

- Work with agri-tech startups for farm-to-market supply chain technology.
- Partner with food processing industries to co-develop branded products.
- Collaborate with government schemes under agri-marketing initiatives like ENAM and PMFME (Pradhan Mantri Formalisation of Micro Food Processing Enterprises).

Conclusion

Marketing water chestnut effectively involves a multifaceted strategy: identifying target markets, investing in brand development, diversifying products, and leveraging digital platforms. With the right promotion, value addition, and outreach, this traditional and seasonal crop can be re-positioned as a modern health food both in domestic and international markets.

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METHODS OF SOIL SAMPLING FOR SOIL ANALYSIS AND NUTRIENT MANAGEMENT

M.A. Sojitra^{1*}, P. M. Kyada², D. B. Balas¹,
N. K. Pampaniya¹ P.A. Damor¹ and A. N. Kunapara¹

¹College of Agricultural Engineering and Technology,
Anand Agricultural University, Godhra, Gujarat

²Farm Science Centre, Likhharati, Sanosara, Bhavanagar, Gujarat

*Corresponding Email: manojsojitra@aau.in

Abstract

Soil sampling methods including grid, random, zone, transect, depth increment, composite, coring, and remote sensing techniques are essential for accurate soil analysis and nutrient management in agriculture. These methods allow farmers to systematically collect representative soil samples, supporting informed decisions on fertilizer application and crop productivity. Soil analysis, covering nutrient assessment, pH, organic matter, texture, and specialized testing, reveals soil fertility and health. Integrating these results with precision nutrient management helps farmers optimize resource use, reduce environmental impact, and sustain soil productivity over the long term.

Introduction

Soil sampling is the foundation of effective nutrient management: it reveals a field's fertility, structure, and composition, and ensures that collected samples accurately represent the area being analyzed (Vullaganti *et al.*, 2025). The method chosen depends on field size, soil variability, and management goals.

Soil Sampling Methods

Method	Approach	Best suited for
Grid sampling	Field divided into equally spaced grids; samples taken at each intersection or center	Large fields with relatively uniform soil
Random sampling	Sampling points selected without a fixed pattern	Fields with heterogeneous soil (varied texture, drainage)
Zone sampling	Field divided into management zones by soil type, topography, or yield history	Targeted management of zones with similar characteristics
Transect sampling	Samples taken at regular intervals along lines across the field (e.g., along slopes or contours)	Assessing soil variability along a gradient
Depth increment sampling	Samples collected at multiple depths in the soil profile	Understanding nutrient distribution and rooting depth
Composite sampling	Multiple cores/subsamples combined into one representative sample	Cost-effective, routine large-scale testing
Soil coring	Intact cores extracted with an auger or core sampler	Studying soil horizons and vertical structure
Remote sensing & GIS	Satellite imagery, aerial surveys, and geospatial analysis of spatial variability	Guiding and enhancing traditional sampling across large areas

Soil Analysis

Once collected, samples are analyzed in the lab across several dimensions:

- **Nutrient analysis** — measures macronutrients (N, P, K) and secondary nutrients (Ca, Mg, S) via chemical extraction, spectroscopy, or ion-selective electrodes, guiding fertilizer formulation.
- **pH measurement** — determines soil acidity/alkalinity; acidic soils (pH < 7) may need lime, alkaline soils (pH > 7) may need sulfur amendments.
- **Organic matter assessment** — measured via combustion or loss-on-ignition; higher organic matter improves structure, water retention, and nutrient cycling.
- **Texture analysis** — determines sand/silt/clay proportions, classifying soil (sandy, loamy, clayey) and predicting water infiltration and drainage behavior.
- **Cation Exchange Capacity (CEC)** — indicates the soil's capacity to retain and exchange nutrient cations; higher CEC means greater fertility potential.
- **Microbial and biological assessment** — evaluates microbial biomass and enzyme activity as indicators of soil ecosystem health.
- **Specialized testing** — addresses specific concerns such as salinity, heavy metals, or soilborne pathogens.

From Analysis to Nutrient Management

Soil analysis directly informs how nutrients are managed in the field:

- **Targeted and balanced fertilization** — soil test results guide fertilizer selection and application rates, correcting deficiencies while maintaining optimal N-P-K ratios to avoid over-application, runoff, and leaching (Xing *et al.*, 2025).
- **Site-specific nutrient management (SSNM)** — using data from grid or zone sampling, fertilizer rates and placement are adjusted to match variability within a field, improving yields while cutting input costs (Sarma *et al.*, 2024).
- **Precision agriculture technologies** — GPS, remote sensing, and variable rate application (VRA) equipment use soil data to apply fertilizer precisely where and how much is needed, minimizing waste and environmental footprint (Vullaganti *et al.*, 2025).
- **Organic and sustainable nutrient sources** — soil analysis highlights opportunities to incorporate compost, manure, green manures, and cover crops, reducing reliance on synthetic inputs while building long-term soil health (Khambalkar *et al.*, 2025).
- **Monitoring and adaptive management** — regular re-testing tracks changes in fertility over time, allowing management strategies to adapt to evolving soil and crop conditions (Kabato *et al.*, 2025).

Conclusion

Choosing the right soil sampling method — matched to a field's size, variability, and management goals — is the first step toward informed, sustainable nutrient management. Combined with thorough soil analysis and precision technologies, it allows farmers and agronomists to optimize fertilizer use, boost crop productivity, and protect soil, water, and air quality for future generations.

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MICROGREENS: THE FUTURE OF NUTRIENT-DENSE URBAN FARMING

Eashwar V

IV Year B.Sc. (Hons.) Horticulture,
Horticultural College and Research Institute, TNAU, Periyakulam,
Theni, Tamil Nadu, India - 625 604.
Corresponding Email: eashwar496@gmail.com

Abstract

Microgreens occupy a unique position at the confluence of nutritional science, controlled environment agriculture, and agri-entrepreneurship. Harvested within 7-21 days of germination, they exhibit nutrient concentrations 4-40 times greater than their mature counterparts, making them a potent functional food. This article examines their botanical identity, phytochemical significance, cultivation protocols, commercial landscape, and their emerging role in India's urban food economy and future space farming programmes.

Introduction

Walk into any upscale restaurant in Chennai, Bengaluru, or Mumbai, and there's a good chance your plate will feature a small, vibrant cluster of greens that aren't just a garnish or a salad leaf. These are microgreens – and despite their tiny size, they're quietly revolutionizing the way fresh food is produced in urban India. Urbanization is happening at breakneck speed, agricultural land is shrinking, and the pandemic has led to a shift towards foods that are functional and immunity-boosting. This perfect storm has created a fertile ground for microgreens. Unlike most crops, they don't require vast tracts of land, specific seasonal timing, or heavy investments. A south-facing balcony, a rack of trays under LED grow lights, or a controlled indoor unit is all you need. This flexibility has attracted entrepreneurs, startups, and institutional growers alike, who see the potential for growth.

Botanical identity and classification

Microgreens are essentially the young seedlings of vegetables, herbs, and cereals that are harvested when the first set of leaves, known as cotyledon leaves, or the first true leaf pair has emerged. This usually happens between 7 and 21 days after germination. They occupy a specific developmental window, falling somewhere in between sprouts and baby greens. Sprouts are consumed whole, including the root, within 2 to 5 days, while baby greens are harvested at 15 to 40 days when they have developed leaves that are around 3 to 4 centimeters long. The key difference between microgreens and these other two categories is that they are typically cut above the growing medium, which means they don't have roots and therefore carry a lower risk of microbial contamination. At the same time, they retain a higher nutrient density compared to baby greens. One of the greatest advantages of microgreens is their taxonomic diversity, which makes them a strong choice for farmers. Many different genera from various families are commonly cultivated, including Brassicaceae, Amaranthaceae, Fabaceae, Apiaceae, Poaceae, and Lamiaceae. Some popular examples of microgreens from these families include radish, broccoli, mustard, cabbage, amaranth, beetroot, spinach, pea, chickpea, fenugreek, coriander, fennel, wheat, barley, and basil.

Nutritional and functional significance

The extraordinary nutrient density of microgreens isn't a coincidence – it's deeply rooted in plant biology. As a seedling, a plant simultaneously taps into the stored reserves in its endosperm and starts producing its own food through photosynthesis and secondary metabolite biosynthesis. This brief but intense biochemical window gives microgreens a massive boost in vitamins, minerals, and antioxidants, far exceeding the levels found in mature vegetables. Research has consistently shown that these concentrations can be 4 to 40 times higher, depending on the specific microgreen species and growing conditions. Microgreens can be grouped based on their dominant phytochemical class, which is closely linked to their visible color - a useful framework for both growers and consumers. For instance: Red and purple microgreens, such as purple radish and red cabbage, are rich in anthocyanins, offering cardiovascular and anti-inflammatory benefits. Orange and yellow microgreens, like yellow mustard and corn, contain beta-carotene and lutein, which help synthesize pro-vitamin A and support visual health. Green microgreens, including pea and fenugreek, are packed with chlorophyll, indoles, saponins, and carotenoids, promoting a wide range of health benefits. White and pale microgreens, such as garlic and onion, are high in allicin and organosulphur compounds, which exhibit antimicrobial activities.

Phytonutrient	Microgreen Source	Primary Health Role
Vitamin C	Mustard, Radish, Kale	Immune function, collagen synthesis
Vitamin E	Sunflower, Amaranth	Antioxidant cell protection
Vitamin K	Broccoli, Pea shoots	Blood coagulation, bone mineralisation
Beta-carotene	Yellow mustard, Corn	Pro-vitamin A; visual health
Lycopene	Red cabbage, Beetroot	Cardiovascular protection
Anthocyanins	Purple radish, Basil	Anti-inflammatory, oxidative defence
Sulforaphane	Broccoli	Documented anti-carcinogenic activity
Allicin	Garlic, Onion, Leek	Antimicrobial; immune modulation
Folate	Spinach, Pea	Cell division; neural development

Table 1. Key phytonutrients in select microgreens and their functional roles**Commercially important varieties**

Radish (*Raphanus sativus*) is a standout crop, ready for harvest in just 7 days. Its peppery flavor and vibrant red and purple varieties make it a premium choice for plating. Broccoli (*Brassica oleracea* var. *italica*), on the other hand, is one of the most researched vegetables, prized for its high sulforaphane content – a compound with proven anti-carcinogenic properties. Sunflower (*Helianthus annuus*) is a nutrient powerhouse, rich in Vitamin E, with thick, nutty stems that benefit from pre-soaking for 6-8 hours to ensure uniform germination. Pea shoots (*Pisum sativum*) offer a sweet, crunchy texture and can be harvested for a second crop when cut at 2-3 cm above the medium, increasing revenue per tray. Fenugreek, or Methi (*Trigonella foenum-graecum*), is a culturally familiar ingredient in South and Central India, with a distinctive bitter-aromatic flavor and high iron and fiber content that makes it easier to adopt in domestic markets. Red amaranth (*Amaranthus cruentus*) is visually striking.

Cultivation Protocol

Start with seeds that are good to eat. Adjust how you prepare them based on the type of seed. Large seeds like sunflower, peas and wheat need to be soaked for 6 to 12 hours. This helps them sprout evenly. Seeds like basil get sticky when soaked so its best not to soak them. Use the

number of seeds for your tray. For seeds like radish and broccoli use about 15 to 20 grams per tray. For seeds like sunflower use 40 to 60 grams. For seeds like beans use 70 to 100 grams. Choose a growing medium. In India coco peat works well because it holds moisture is light and has a pH level (5.8 to 6.2). You can also use jute or hemp mats if you are not using soil. Fill the tray to a depth of 1 to 1.5 inches. Do not press the medium down hard. Sow the seeds by spreading them on the moist surface. Press them down gently so they have contact with the medium. Do not cover the seeds. For the 3 days cover the tray to keep it dark. Keep the temperature between 20 to 25°C. Spray a water if the surface gets dry. Once the seeds start to grow give them light. You can use light or LED lights placed 15 to 20 cm above the tray. Switch to watering, from the bottom to prevent issues. Harvest your microgreens between 7 to 14 days. Cut them above the medium with a clean tool when the true leaves come out. Rinse them gently let them air dry and store them at 4 to 6°C. They will stay fresh for 5 to 7 days. Many people prefer to sell trays because they stay fresh for a longer time.

Advantages and Limitations

Microgreens give profits in small areas. They can produce 100 to 200 grams per tray in 7 to 14 days. They use up to 95% water. You can grow them inside all year round. Get a steady income every week. They do not last long. Only 5 to 7 days. They have to be sold in markets because the cold storage and transportation in India are not very good. There is also a risk of problems when it is humid like with *Pythium* and *Fusarium*. People do not know much about microgreens. They are expensive ₹200 to ₹600, for 100 grams. This means only people who are willing to pay more will buy them.

Conclusion

Microgreens might just fit how cities in India eat tomorrow – backed by research, able to grow at scale, kind on resources, fitting tight spaces and city limits. Packed with plant compounds proven by labs, they sprout fast, often before two weeks pass, needing little to start, so almost anyone can grow them or sell them. With better refrigerated transport arriving slowly, people learning more about what they consume, schools and hospitals starting to order bulk, these small leafy shoots could shift from plate decoration to daily nourishment. Facts support their value already. Buyers are beginning to show up. Those who step in now might find space before others arrive.

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**MIMIMUM SUPPORT PRICE AND CLIMATE MISMATCH:
RETHINKING CROP CHOICE FOR SUSTAINABLE AGRICULTURE****Tarni Sahu^{1*} and Surbhi Suman²**¹Department of Agriculture Extension Education, JNKVV, Jabalpur (M.P.)²Bachelor of Agriculture, SHUATS, Allahabad (U.P.)*Corresponding Email: tarnis1092@gmail.com**Introduction**

Minimum Support Price (MSP) is promised by the government for any agricultural crop whereas the issue price is the price at which Government issue the same agricultural crop. Based on the recommendations of the Commission for Agricultural Costs and Prices (CACP), the Department of Agriculture and Co-operation, Government of India. currently announced for 24 commodities. the Agricultural Prices Commission (renamed as the Commission for Agricultural Costs and Prices (1985) was established in 1965 for advising the Government on agricultural prices policy on a continuing basis. The thrust of the policy in 1965 was to evolve a balanced and integrated structure to meet the overall needs of the economy and with due regard to the interests of the producers and the consumers. The first Commission was headed by Prof M L Dantwala and in its final report the Commission suggested the Minimum Support Prices for Paddy. Report of National Commission for Farmers (NCF) had recommended that MSP should be at least 50% more than the weighted average cost of production.

MSP and climate Change

Paddy cultivation emitted approximately 3.2 million tonnes of methane in 2020 – accounting for 23% of India's total agricultural methane emission. This is the direct climate cost of MSP-driven rice monoculture. Flooding creates anaerobic condition in rice field, leading to the proliferation of methanogenic bacteria and the production of methane; more than 75 % of global rice cultivation takes place in flooded fields. agriculture contributes 18% to India's total emissions; of this, 18% stems specifically from rice production, while 21% comes from nitrogen-based emissions (resulting from fertilizers, which are heavily used for MSP crops). Research indicates that a 1°C rise in temperature can cause rice yields to drop by up to 14.6%—meaning the very crop promoted by the MSP is also the most vulnerable to climate change. It is a vicious cycle: MSP → rice monoculture → methane emissions → climate change → declining rice yields. MSP-driven paddy-wheat cycle → short harvest window → stubble burning → air pollution + additional carbon emissions. Techniques such as Alternate Wetting and Drying (AWD) and mid-season drainage can significantly reduce methane emissions while also conserving water; these could be linked to MSP in future policies (e.g., "climate-smart MSP incentives").

Rice – Wheat MSP: Importance and challenges

The MSP for rice and wheat has played a central role in shaping India's agricultural economy since the Green Revolution era. By guaranteeing a fixed procurement price, MSP provided farmers with income stability and helped India transition from a food-deficit nation to one of the world's largest producers of rice and wheat. This assurance encouraged large-scale adoption of high-yielding varieties, expanded irrigation infrastructure, and built a robust procurement and storage network through the Food Corporation of India (FCI), ensuring food security for the country's Public

Distribution System. However, this same policy structure has generated significant challenges over time. The most pressing is environmental: continuous rice-wheat cultivation, incentivized by assured MSP procurement, has led to severe groundwater depletion, particularly in Punjab and Haryana, where a large share of cropped area remains locked into this single cycle year after year. The short window between paddy harvesting and wheat sowing has also driven the widespread practice of stubble burning, contributing significantly to seasonal air pollution in North India. Beyond environmental costs, the rice-wheat MSP system has entrenched monoculture, discouraging crop rotation and diversification. This has resulted in declining soil fertility, increased dependency on chemical fertilizers, and reduced agro-biodiversity. Furthermore, MSP benefits remain geographically skewed, with effective procurement concentrated in a handful of states, leaving farmers in other regions without comparable price assurance despite growing the same crops.

Regional Climate Diversity and MSP

India's vast geographical expanse encompasses remarkable agro-climatic diversity, officially classified into 15 distinct agro-climatic zones and 72 sub-zones by the Planning Commission and National Remote Sensing Agency. Each zone is defined by its unique combination of rainfall pattern, temperature range, soil type, and water availability, making certain crops naturally more suited to specific regions — for instance, coconut and rice in coastal areas, or apples and temperate fruits in Himalayan regions. MSP, however, operates as a uniform, nationally applicable price mechanism that does not account for this regional variation. As a result, farmers across ecologically distinct zones often gravitate toward the same MSP-backed staple crops, regardless of whether these crops align with their local climatic and soil conditions. Water-abundant eastern states such as Bihar, West Bengal, and Assam may find rice cultivation naturally sustainable, while the same crop choice in water-stressed regions of Punjab, Haryana, or parts of central India accelerates groundwater depletion and soil stress. This disconnect undermines the very purpose of agro-climatic zone planning, which was originally designed to guide farmers toward crops best suited to their region's resource base, thereby ensuring efficient utilization of land, water, and technology. When a blanket pricing policy overrides zone-specific scientific recommendations, the outcome is a cropping pattern driven more by assured income than by ecological suitability.

Intercultural Operations and Ease of Cultivation in Relation to MSP

MSP-driven cropping decisions are not shaped by price incentives alone; the relative ease of growing rice and wheat compared to alternative crops plays an equally significant role in reinforcing this cycle. Over decades, rice and wheat cultivation has become highly mechanized, supported by tractors, combine harvesters, seed drills, and threshers, along with well-established irrigation infrastructure. This mechanization, combined with decades of research through agricultural universities and Krishi Vigyan Kendras, has made the entire package of practices for rice and wheat widely accessible and low-risk for farmers. In contrast, millets and pulses—many of which are naturally suited to intercropping and mixed cropping systems—remain largely dependent on manual labour. The absence of specialized harvesting tools, combined with poor availability of quality seeds and weak market infrastructure for these crops, further discourages farmers from adopting them, regardless of MSP announcements. This disparity directly affects intercultural operations such as crop rotation and intercropping. When farmers commit their entire landholding to a guaranteed MSP crop grown two to three times a year, there is little scope left for practices that would otherwise improve soil health, break pest cycles, and support natural nutrient

replenishment. Punjab's cropping pattern illustrates this clearly, where a large majority of the total cropped area remains locked into a continuous wheat-paddy cycle, leaving minimal room for diversification or rotational practices. Thus, the persistence of rice and wheat is driven not only by assured pricing, but by an entire ecosystem of mechanization, infrastructure, and institutional support that alternative crops have yet to receive.

Potential Alternatives

Recognizing the limitations of a rice-wheat-centric MSP system, the government has introduced several schemes aimed at diversifying crop support beyond staple grains. The most significant of these is the Pradhan Mantri Anna data Aay Sanrakshan Abhiyan (PM-AASHA), launched in 2018 as an umbrella scheme to extend price assurance to pulses, oilseeds, and copra. It operates through three components: the Price Support Scheme (PSS), involving direct government procurement; the Price Deficiency Payment Scheme (PDPS), which compensates farmers for the difference when market prices fall below MSP; and the Private Procurement Stockist Scheme (PPSS). In the 2025-26 budget, the government committed to procuring 100% of the production of tur, urad, and masoor by 2028-29, alongside an increased financial guarantee under PM-AASHA, signalling a stronger push toward pulses self-sufficiency. In the Kharif 2025-26 season, the highest MSP increases were granted to niger seed and ragi, exceeding the hikes given to paddy and wheat, in an attempt to make alternative crops more financially attractive. The government has also promoted millets more broadly under the "Shree Anna" initiative, particularly following the International Year of Millets in 2023, through seed hubs, branding support, and inclusion of millets in the Public Distribution System. The Shanta Kumar Committee (2015) noted that MSP benefits effectively reach only about 6% of farmers nationally, largely due to weak APMC market infrastructure, indicating that these schemes, while promising, require stronger last-mile procurement and market linkages to achieve meaningful impact on cropping patterns.

Reform Suggestions

Addressing the climate mismatch embedded in India's MSP policy requires structural reform rather than incremental adjustments alone. A central and long-debated proposal is the adoption of the Swaminathan Commission's recommendation, made in 2006, that MSP should be set at a minimum of 50% above the comprehensive cost of production, known as C2, which accounts not only for direct input costs but also the imputed value of family labour, rent on owned land, and interest on fixed capital. The current formula, based on A2+FL, excludes these components, resulting in a significant gap between demanded and announced prices; for the 2025-26 kharif season, the C2+50% rate for paddy would have been approximately ₹3,135 per quintal, against an announced MSP of ₹2,369 per quintal. A second major demand from farmer organizations is for a legal guarantee of MSP across all notified crops, rather than the current system where MSP functions merely as a recommended price without enforceable procurement. Without legal backing, farmers in regions with weak procurement infrastructure are often compelled to sell below MSP in open markets, undermining the policy's intended protection. Beyond pricing mechanisms, reform should focus on climate-aligned incentive structures, such as offering premium or bonus MSP rates for millets and pulses in regions where rice-wheat cultivation is ecologically unsustainable, rather than applying uniform national rates.

Conclusion

MSP has played a vital role in ensuring food and income security since the Green Revolution, but its uniform, staple-centric design has created a growing mismatch with India's diverse agro-

climatic realities. This has resulted in groundwater depletion, soil degradation, stubble burning, and the continued neglect of climate-resilient crops such as millets and pulses, leaving farmers caught between economic security and environmental sustainability. While schemes like PM-AASHA and Shree Anna signal positive movement, meaningful change requires structural reforms — including cost-based pricing, stronger procurement infrastructure, and region-specific incentives. The way forward lies not in abandoning MSP, but in reimagining it as a climate-responsive tool that secures both farmer livelihoods and long-term agricultural sustainability.

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LARGE EXPERIMENTS IN SMALL BLOCKS: A CASE STUDY

Vankudoth Kumar^{1,2*}, Sukanta Dash², Med Ram Verma², Anil Kumar³,
Anurag Rawat^{1,2} and Lunganlung PG^{1,2}

¹The Graduate School, ICAR-IARI, New Delhi-110012

²ICAR-IASRI, Pusa, New Delhi-110012

³Krishi Bhavan, ICAR, New Delhi-110001

*Corresponding Email: kumarvankudoth51@gmail.com

Large five-level factorial experiments are difficult not only because they contain many treatments, but also because field plots are rarely uniform. Soil fertility, slope, drainage, moisture, and previous crop history can create systematic differences across an experimental area. A confounded factorial design addresses this problem by retaining the complete treatment set and arranging it in smaller blocks. Selected factorial effects, preferably complex interactions of limited practical importance, are deliberately combined with block effects so that major treatment comparisons can be protected from field heterogeneity. This article illustrates the approach for a five-factor cotton-management experiment containing $5^5 = 3,125$ treatment combinations. Depending on the chosen block parameter, the treatments can be organized in blocks of 5, 25, 125, or 625 plots. The `lfebd5.cf()` and related functions in the `lfebd3` R package provide a reproducible way to construct the arrangement and inspect the independent confounded effects. The method improves manageability and local precision, but it requires careful selection and transparent reporting of the effects sacrificed to blocking.

Keywords: Five-level confounded factorial; blocking; cotton management; R package.

Introduction

A large factorial experiment may be statistically complete yet poorly executed if field variation is ignored. Plots at the top of a field can differ from plots at the bottom; irrigation may move unevenly; and soil texture can change across short distances. When thousands of treatments are involved, these gradients can obscure genuine treatment differences.

Confounding is a blocking strategy for this situation. Unlike fractionation, it does not discard treatment combinations. All treatments remain in the experiment, but selected factorial effects are made inseparable from block differences. The purpose is to place nearby or otherwise similar experimental units in the same block and thereby reduce the unexplained variation affecting the comparisons of greatest scientific interest.

Constructing the blocked design in R

For n five-level factors, the `lfebd5.cf(n, r)` function available in the `lfebd3` R package arranges all 5^n treatment combinations in blocks of size 5^c (Kumar *et al.*, 2026). The number of blocks is therefore 5^{n-c} . For a five-factor design with $c = 2$, each block contains 25 treatments and the complete experiment contains 125 blocks. The independent confounded effects should be obtained and reviewed before implementation. If the experimental site exhibits variation in two directions, a row-column arrangement may provide additional control beyond a one-way block structure (Yadav *et al.* 2026).

```
library(lfebd3)
cotton_blocked <- lfebd5.cf(n = 5, c = 2)
cotton_blocked
lfebd5.cf_independent_confounding(n = 5, c = 2)
```

Case study: a five-factor cotton experiment

Consider a cotton study in which variety, nutrient level, irrigation, plant density, and growth-regulator dose are examined together. The complete design contains 3,125 treatments, but these treatments can be placed in relatively homogeneous local blocks rather than treated as one undivided field.

The choice depends on field size, machinery, irrigation layout, labour organization, and the spatial scale of heterogeneity. Blocks should be small enough to be internally similar but large enough to support feasible field operations. If the site has variation in two directions, a row-column arrangement may provide additional control beyond a one-way block structure.

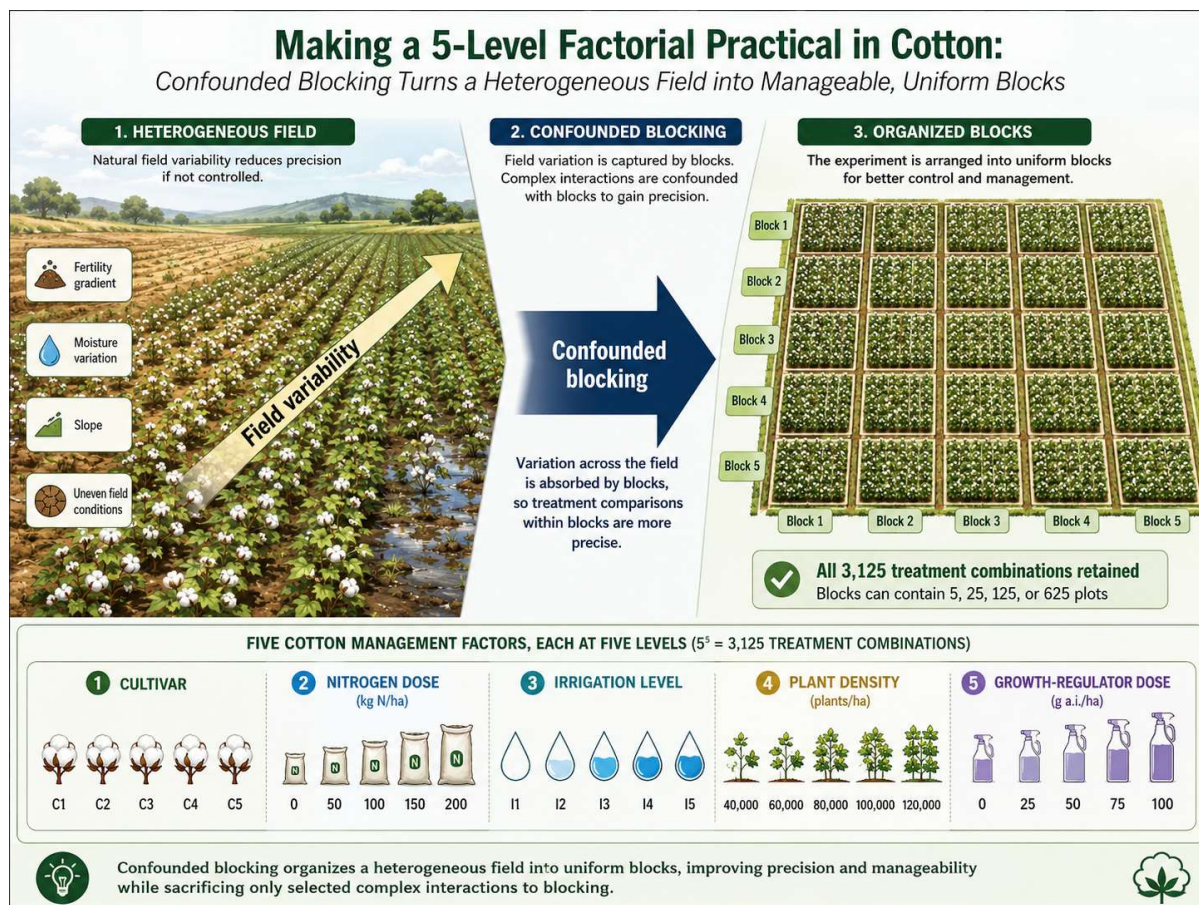


Figure 1. Conceptual arrangement of a heterogeneous field into blocks for a five-level confounded factorial experiment.

Protecting important effects

The effects assigned to blocks should be chosen deliberately. Main effects and scientifically important two-factor interactions are normally protected, while complicated higher-order interactions may be considered for confounding when prior knowledge suggests that they are less

important. The independent confounded effects should be obtained and reviewed before implementation. The resulting factorial block arrangement and its confounding structure may also be examined using the diagnostic and characterization tools available in the FactChar R package (Dash *et al.* 2025).

Blocking does not compensate for weak field practice. Randomization within the allowed design structure, uniform measurement procedures, accurate plot identification, and complete block records remain essential. When blocks are spread across locations or dates, those additional sources of variation should be included in the statistical model.

Conclusion

Five-level confounded factorial designs provide a practical way to conduct complete multi-factor experiments under non-uniform field conditions. In the cotton illustration, all 3,125 treatment combinations are retained and can be organized into blocks whose size matches the scale of field variation and operational capacity. The `lfebd5.cf()` function supports reproducible construction, while the independent confounding output identifies the effects sacrificed to blocking. The design is most useful when block formation is based on real field knowledge and when important treatment effects are protected explicitly before the experiment begins.

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**MICROGREENS IN VEGETABLES: NATURE'S TINY
NUTRITIONAL POWERHOUSE****Udham Singh*, Shweta Soni, Manish Kumar Singh and Ajeet Singh**

Department of Vegetable Science, College of Horticulture,
Banda University of Agriculture and Technology, Banda, Uttar Pradesh, India (210001).

*Corresponding Email: 26us0202@gmail.com

Abstract

There is a quiet revolution unfolding in gardens, kitchens, urban farms, and laboratory greenhouses worldwide, and its protagonist measures no more than five to ten centimetres tall. Microgreens are the young, tender seedlings of vegetables, herbs, and other edible plants harvested at the cotyledon or first true-leaf stage that have emerged from relative obscurity in high-end restaurant kitchens to become one of the fastest-growing segments of the global specialty produce market. Their appeal is built on a compelling convergence of visual vibrancy, concentrated flavour, exceptional nutritional density, and remarkable versatility that extends from the gourmet dining room to the pharmaceutical laboratory. The global microgreens market, valued at approximately USD 1.3 billion in 2020, is projected to expand at a compound annual growth rate of 7.5 to 11.1% through 2030, driven by increasing consumer awareness of functional foods, rising demand for plant-based nutrition, and the scalability of indoor vertical farming systems that make year-round, climate-independent microgreen production feasible at both small and commercial scales (Grand View Research, 2021). This article surveys the most significant vegetable microgreens, their growth stages, nutrient composition, and documented health benefits, and maps their expanding applications across culinary, nutraceutical, pharmaceutical, cosmetic, and agricultural industries.

Introduction

The term 'microgreen' was first widely adopted in the culinary world in California during the 1980s and 1990s, when pioneering chefs began experimenting with immature seedlings as plate garnishes for their aesthetic appeal and intense flavour concentration. However, the scientific investigation of their nutritional profile did not begin in earnest until the 2000s, when researchers at the United States Department of Agriculture and various academic institutions began quantifying the startling concentrations of vitamins, minerals, and phytonutrients that these tiny plants accumulate in the brief window between germination and first true-leaf development. A landmark study by Xiao *et al.*, (2012), published in the *Journal of Agricultural and Food Chemistry*, demonstrated that microgreens of 25 commercially available species contained vitamin C, E, and K concentrations between 4 and 40 times higher than those found in the mature leaves of the same plants — findings that fundamentally repositioned microgreens from culinary curiosity to a subject of serious nutritional science. Unlike sprouts, which are germinated seeds consumed in their entirety, root and all, typically after two to five days, microgreens are grown in a growing medium (soil, coco coir, hydroponic mats) and harvested above the root line at seven to twenty-one days after sowing, after the cotyledons have fully expanded but generally before the first true leaf reaches its full size. This distinction is agronomically and food-safety-relevant: sprouts are produced in warm, moist, oxygen-limited conditions that are conducive to bacterial contamination, while microgreens are grown in open, well-ventilated environments with lower

microbial risk. The harvest is made with scissors just above the medium surface, and the green portions like cotyledons, hypocotyl, and sometimes the first true leaf that constitute the edible product.

Vegetable Plants Consumed as Microgreens: Species and Growth Stages

Virtually any plant whose seedling cotyledons and young stem are edible can theoretically be consumed as a microgreen; however, a defined core of vegetable species has emerged as commercially and nutritionally dominant. These span five botanical families like Brassicaceae, Cucurbitaceae, Amaranthaceae, Apiaceae, and Fabaceae, each contributing distinct flavour profiles, visual characteristics, and nutritional specialisations. Table 1 below presents the key vegetable species consumed as microgreens, the specific growth stage at which they are harvested, and their characteristic sensory and nutritional attributes.

Table 1: Major Vegetable Plants Consumed as Microgreens — Species, Family, Harvest Stage, and Characteristics

Common Name	Botanical Name	Family	Days to Harvest	Harvest Stage	Flavour / Notable Character
Brassicaceae (Crucifer Family) — Rich in glucosinolates, sulforaphane, vitamins C and K					
Radish	<i>Raphanus sativus</i>	Brassicaceae	6–10	Cotyledon	Intensely peppery and spicy; red-stemmed varieties have high anthocyanin content
Broccoli	<i>Brassica oleracea</i> var. <i>italica</i>	Brassicaceae	7–12	Cotyledon	Mild, slightly earthy; highest sulforaphane content of all microgreens
Cabbage	<i>Brassica oleracea</i> var. <i>capitata</i>	Brassicaceae	7–10	Cotyledon	Mild, slightly sweet; red cabbage varieties rich in anthocyanins
Kohlrabi	<i>Brassica oleracea</i> var. <i>gongylodes</i>	Brassicaceae	8–12	Cotyledon	Mildly sweet with a hint of turnip; purple varieties highly decorative
Kale	<i>Brassica oleracea</i> var. <i>acephala</i>	Brassicaceae	8–12	Cotyledon	Mild, green, slightly bitter; one of the richest sources of vitamin K
Cucurbitaceae (Gourd Family) — High in beta-carotene, vitamin E, and cucurbitacins					
Cucumber	<i>Cucumis sativus</i>	Cucurbitaceae	7–12	Cotyledon	Fresh, mild, and slightly sweet; thick cotyledons with excellent crunch
Melon	<i>Cucumis melo</i>	Cucurbitaceae	8–12	Cotyledon	Delicate, subtly sweet; fragrant; rich in beta-carotene
Bottle Gourd	<i>Lagenaria siceraria</i>	Cucurbitaceae	8–14	Cotyledon	Neutral, slightly grassy; high in water content and minerals
Amaranthaceae / Chenopodiaceae — High in betalains, oxalates, vitamins C and A					
Amaranth	<i>Amaranthus tricolor</i>	Amaranthaceae	7–12	Cotyledon	Earthy, mildly sweet; dramatic red-magenta colouration from betalain pigments
Beetroot	<i>Beta vulgaris</i>	Amaranthaceae	10–14	Cotyledon	Earthy, slightly sweet; deep red-purple stems; exceptionally high in betalains
Spinach	<i>Spinacia oleracea</i>	Amaranthaceae	8–14	Cotyledon	Mild, delicate spinach flavour;

Common Name	Botanical Name	Family	Days to Harvest	Harvest Stage	Flavour / Notable Character
					very tender; rich in folate and iron
Fabaceae (Legume Family) — High in protein, folate, vitamin C, and dietary fibre					
Pea Shoot	<i>Pisum sativum</i>	Fabaceae	10–16	Cotyledon + tendrils	Sweet, green, delicate flavour; tendrils add texture; popular in Asian cuisines
Fenugreek	<i>Trigonella foenum-graecum</i>	Fabaceae	8–12	Cotyledon	Mildly bitter with characteristic aroma; high in diosgenin and iron
Apiaceae / Asteraceae / Other Families					
Coriander	<i>Coriandrum sativum</i>	Apiaceae	12–18	Cotyledon	Intensely citrusy and aromatic; slower to germinate; distinctive linalool aroma
Amaranth (Green)	<i>Amaranthus cruentus</i>	Amaranthaceae	7–12	Cotyledon	Mild, earthy; dense nutrition; excellent as a protein-rich microgreen base

Days to harvest may vary by temperature (optimal 18–24°C), light intensity, and growing medium. Cotyledon stage = fully expanded seed leaves; 1st true leaf = first species-specific leaf appears.

Nutrient Content of Microgreens

The nutritional profile of microgreens is perhaps their most scientifically remarkable attribute. Despite their diminutive size, microgreens accumulate exceptionally high concentrations of vitamins, minerals, polyphenols, carotenoids, and other bioactive compounds within their cotyledon tissue during the brief burst of metabolic activity that accompanies germination and early seedling growth. The physiological basis for this concentration lies in the seed's investment: the nutrient reserves stored within the seed are mobilised and, combined with the products of the seedling's own nascent photosynthetic and biosynthetic activity, they are channelled into the rapidly expanding cotyledon tissue. The result is a remarkable density of micronutrients per unit dry weight that far exceeds that of the corresponding mature vegetable (Xiao *et al.*, 2012; Kyriacou *et al.*, 2016).

A foundational comparative study by Xiao *et al.* (2012) analysed 25 commercially available microgreen species for vitamin C, E (alpha-tocopherol and total tocopherols), K, and beta-carotene content, comparing values with published data on mature vegetable leaves. The results were striking: vitamin C concentrations in microgreens ranged from 20.4 mg/100 g FW (garnet amaranth) to 147.0 mg/100 g FW (cilantro/coriander), compared to values of 5–30 mg/100 g FW in corresponding mature leaves. Vitamin E (as alpha-tocopherol) ranged from 0.9 to 63.5 mg/100 g FW, with daikon radish microgreens exhibiting the highest values and beta-carotene ranged from 0.6 to 12.1 mg/100 g FW. Vitamin K ranged from 0.6 to 4.1 µg/g FW. Critically, all these concentrations substantially exceeded those found in mature plants, with some microgreens containing up to 40-fold higher concentrations.

Usage of Microgreens Across Different Industries

Culinary and Food Service Industry

The culinary applications of microgreens represent the most commercially mature and economically largest segment of the market. High-end restaurants and professional chefs prize

microgreens for their intense flavour concentration a single teaspoon of broccoli microgreens delivers a sulphurous, brassica intensity that might take several tablespoons of mature florets to achieve, combined with their striking visual diversity of colours, textures, and shapes. Microgreens are routinely deployed as plate garnishes, salad components, sandwich fillings, soup toppings, pizza ingredients, and as flavour enhancers in cold dishes. Their delicate texture and perishability (shelf life of 7–14 days at 4°C) have driven innovation in modified atmosphere packaging and controlled atmosphere storage systems specifically designed to extend their commercial window (Di Gioia *et al.*, 2017).

Nutraceutical and Functional Food Industry

The exceptional nutrient density of microgreens has made them natural candidates for the rapidly expanding nutraceutical and functional food sector. Microgreen powders are produced by freeze-drying or spray-drying to preserve bioactive compound integrity, are increasingly incorporated as nutritional fortifiers in protein supplements, meal replacement powders, green superfood blends, infant formula fortifiers, and functional beverages. Broccoli microgreen powder, standardised for sulforaphane content, has been commercialised as a nutraceutical supplement in several markets and is being evaluated in clinical trials for cancer chemoprevention and neuroprotection. The global demand for 'clean label' functional foods products delivering health benefits through natural, minimally processed ingredients creates a strong market pull for microgreen-based ingredients (Paradiso *et al.*, 2018).

Pharmaceutical and Biomedical Industry

The pharmaceutical industry's interest in microgreens centres principally on the extraction and purification of high-value phytochemicals for drug development and clinical nutrition applications. Sulforaphane from broccoli microgreens is the most advanced pharmaceutical candidate, with ongoing clinical trials evaluating its efficacy in autism spectrum disorder, schizophrenia, breast cancer prevention, and *H. pylori* eradication (Talalay *et al.*, 2007). Glucosinolate extracts serve as research tools and potential pharmaceutical intermediates. Betalain extracts from beetroot and amaranth microgreens are under investigation as natural antioxidant pharmaceutical excipients and as colourants for pharmaceutical tablets and capsules that offer superior stability to synthetic azo dyes. Microgreens grown under controlled conditions provide a consistent, standardisable source of these compounds — an important advantage over field-grown mature plants whose phytochemical content is highly variable (Ebert, 2022).

Cosmetic and Personal Care Industry

The cosmetics industry has been a relatively recent but rapidly growing adopter of microgreen extracts and oils. The high concentrations of tocopherols (vitamin E), ascorbic acid, carotenoids, and polyphenols in microgreen extracts make them attractive antioxidant actives for anti-ageing serums, moisturisers, and sun-protective formulations. Radish microgreen extract, rich in anthocyanins and isothiocyanates, has been incorporated into hair-care products for its reported scalp anti-microbial and circulation-stimulating effects. As the 'green beauty' movement accelerates, microgreen-derived ingredients represent a compelling proposition for brands seeking naturally derived, science-backed, and sustainably produced active ingredients (Turner *et al.*, 2020).

Animal Feed and Aquaculture Industry

Microgreens and their by-products (root mats, spent growing media residues) are gaining recognition as nutritional supplements in animal feed and aquaculture systems. In aquaculture,

microgreen-derived carotenoid concentrates (particularly astaxanthin precursors from certain algae-microgreen combinations) are being investigated as natural pigmentation enhancers in salmonid fish diets. The short production cycle and scalability of microgreen systems make them attractive candidates for integrated crop-livestock farming models aimed at reducing synthetic additive use.

Agricultural Research and Biofortification

In the context of agricultural science, microgreens serve as rapid-cycling model systems for screening genotype × environment interactions affecting phytochemical accumulation, allowing researchers to evaluate large germplasm collections for nutritional traits in a fraction of the time required for mature-plant evaluation. The United States Department of Agriculture's investigations of microgreen nutritional profiles across hundreds of commercially available varieties have provided foundational datasets that underpin both breeding and agronomy programmes (Xiao *et al.*, 2012). Biofortification research, the deliberate improvement of crop nutritional value through breeding or agronomic means has increasingly utilised microgreen systems to evaluate the effects of selenium, zinc, and iodine biofortification treatments on seedling accumulation efficiency, with implications for addressing micronutrient deficiency in food-insecure populations (Weber *et al.*, 2017).

Conclusion and Future Prospects

Microgreens occupy a singular position in contemporary food science, simultaneously a traditional culinary garnish, a cutting-edge nutraceutical ingredient, a model system for phytochemical research, and an accessible tool for household nutrition. The scientific literature accumulated over the past two decades has established, with considerable rigour, that these small seedlings contain concentrations of vitamins, antioxidants, polyphenols, and functional phytochemicals that substantially exceed those of corresponding mature vegetables sometimes by orders of magnitude. The evidence linking these concentrated bioactives to demonstrable health benefits from sulforaphane's anti-cancer and neuroprotective properties, to anthocyanins' cardiovascular benefits, to betalains' anti-inflammatory activities that provides a compelling scientific foundation for the culinary and therapeutic enthusiasm that microgreens have attracted. The commercial landscape surrounding microgreens is expanding rapidly and in multiple directions simultaneously. For the individual consumer, the message is refreshingly simple and actionable: incorporating a diverse variety of microgreens from broccoli and radish through pea shoots, amaranth, and beetroot, into the daily diet represents one of the most nutritionally efficient choices currently available in the fresh produce market. A small handful of mixed microgreens, added to a salad, sandwich, smoothie, or soup, delivers a concentrated burst of vitamins, minerals, antioxidants, and functional phytochemicals in a low-calorie, high-flavour package that is as appealing to the palate as it is beneficial to the body. In a world grappling simultaneously with undernutrition, micronutrient deficiency, chronic disease burden, and environmental sustainability challenges, the humble microgreen, tiny, fast-growing, and extraordinarily potent that emerges as one of nature's most efficient answers.

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DROUGHT CONDITIONS ACROSS INDIA DURING 2026: IMPLICATIONS FOR AGRICULTURAL PRODUCTIVITY AND FARMERS' LIVELIHOODS

P. Bhasker

Department of Botany and Plant Physiology,
CCS Haryana Agricultural University, Hisar-125 004 (Haryana), India

*Corresponding Email: bhaskarhau@gmail.com

Abstract

The southwest monsoon of 2026 had one of the weakest onset seasons among those recorded in the last decade, resulting in drought throughout several parts of India. Weak rainfall patterns in June, slow movement of the monsoons, and strong El Niño patterns have greatly impacted the kharif crop season. By the beginning of July, almost 41% of India's geographical coverage is affected by drought and near-drought situation, especially in the central, western, eastern, and north-eastern parts of the country. Drought decreased soil moisture, delayed sowing of important crops like rice, pulses, oilseeds, and cotton, and increased reliance on irrigation in rainfed zones. Considering that more than 55-60% of cultivated lands of India depend on monsoon rainfall, the current drought situation is highly challenging to agriculture, food production, water management, and rural livelihoods. Small farmers and marginal farmers are the most affected due to lack of irrigation facilities and finance.

Keywords: Agricultural productivity, climate change, drought, El Niño, kharif crops

Introduction

Agriculture remains the backbone of the Indian economy, supporting nearly half of the country's population and contributing significantly to food security. Despite considerable expansion of irrigation infrastructure, about 55–60% of India's cultivated land remains dependent on monsoon rainfall, making the southwest monsoon responsible for nearly 75% of annual precipitation a critical determinant of agricultural productivity and rural livelihoods. During 2026, India experienced one of the weakest southwest monsoon onsets in the past decade, with rainfall approximately 64% below the long-term average by mid-June, largely due to delayed monsoon advancement and strengthening El Niño conditions over the equatorial Pacific Ocean. The resulting moisture deficit disrupted the timely sowing of major kharif crops, including rice, maize, cotton, soybean, pulses, and groundnut, by reducing soil moisture, impairing seed germination, and shortening the crop-growing period, particularly in rainfed regions. Furthermore, climate change has intensified the frequency and severity of extreme weather events, increasing rainfall variability and the occurrence of droughts and floods. The 2026 drought therefore highlights the growing vulnerability of Indian agriculture to climate variability and underscores the urgent need for climate-resilient farming practices, efficient water management, and adaptive policy interventions.

Drought Scenario across India During 2026

The 2026 drought developed rapidly following one of the weakest southwest monsoon onsets in the past decade. Delayed monsoon progression and prolonged dry spells during June resulted in widespread moisture stress across central, western, eastern, and northeastern India, representing

a significant deterioration compared with the localized drought conditions observed during the same period in 2025. Rainfall deficiency was the primary driver of drought development, with major agricultural states such as Madhya Pradesh, Maharashtra, Chhattisgarh, Odisha, Bihar, Jharkhand, West Bengal, and parts of northeastern India receiving substantially below-normal rainfall. The resulting decline in soil moisture adversely affected crop establishment and increased agricultural water stress, particularly in rainfed regions, whereas parts of northwestern and southern peninsular India experienced relatively better rainfall. According to the National Drought Monitor (IIT Gandhinagar), nearly 41.2% of India's geographical area was under drought or near-drought conditions by early July 2026, compared with 19.6% a month earlier. Western India recorded the highest drought coverage (71%), followed by northeastern (62%), central (53%), and northern (46%) regions. The Ministry of Agriculture and Farmers' Welfare identified 111 districts across 12 states as highly vulnerable due to below-normal rainfall and inadequate irrigation infrastructure, with many districts having irrigation coverage below 25%. Weekly drought assessments indicated a rapid transition from mild moisture stress to moderate, severe, and extreme drought during the critical kharif sowing period, increasing the vulnerability of rainfed agriculture.

The weak monsoon was largely attributed to the strengthening El Niño phenomenon, which disrupts atmospheric circulation and suppresses moisture transport over the Indian subcontinent. Climate forecasts suggested that the 2026 El Niño could become one of the strongest in recent decades, increasing the likelihood of continued rainfall deficits. Comparisons with previous drought years, including 1987, 2009, and 2015, further raised concerns about reduced agricultural productivity, delayed crop establishment, and heightened risks to food security and farmers' livelihoods.

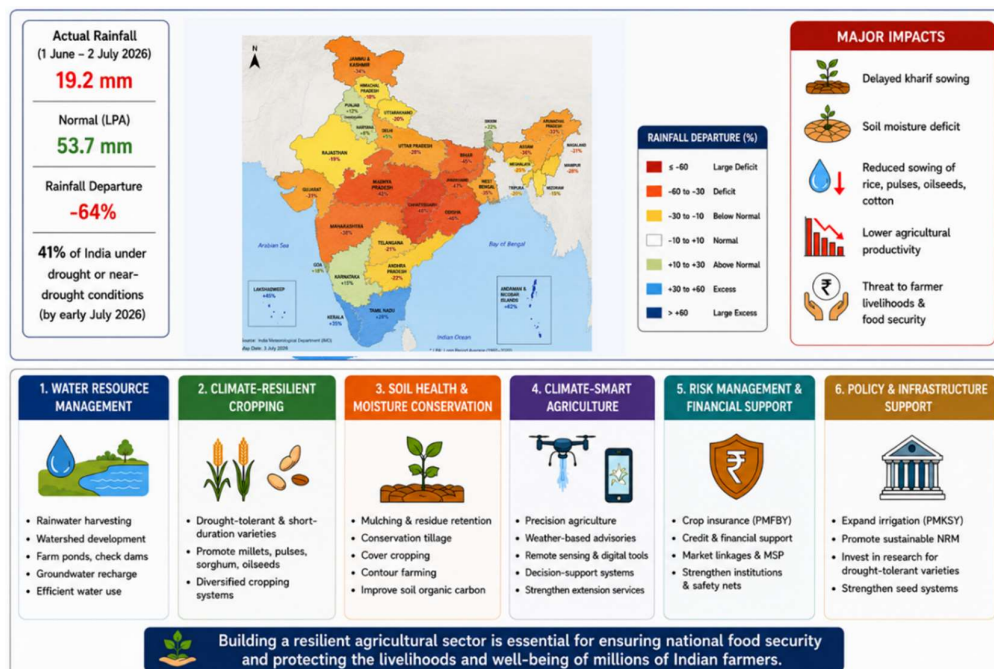


Figure 1. Summary of the 2026 drought scenario in India showing rainfall deficit (June 1–July 2, 2026), major impacts on agricultural productivity and farmers' livelihoods, and key climate-resilient adaptation strategies for sustainable agriculture.

Impacts on Agricultural Productivity

The 2026 drought severely affected agricultural productivity by disrupting the timely sowing of kharif crops due to delayed monsoon rainfall and widespread moisture stress. By the end of June, the total kharif sown area declined from 23.65 million ha in 2025 to 18.27 million ha in 2026, representing a reduction of nearly 23%. Major crops, including rice, pulses, oilseeds, cotton, and coarse cereals, recorded significant declines in sown area, with oilseeds experiencing the largest reduction. Inadequate soil moisture delayed field operations, reduced seed germination, and impaired crop establishment, particularly in rainfed regions.

Delayed sowing shortened the crop-growing period, resulting in reduced biomass accumulation, poor root development, lower photosynthetic efficiency, and diminished grain yield. Prolonged drought during reproductive stages adversely affected flowering, pollination, and grain filling, leading to greater yield variability. Soil moisture deficits also reduced nutrient availability, microbial activity, and water-use efficiency while accelerating leaf senescence and soil degradation. In many drought-affected regions, declining reservoir storage and groundwater levels limited irrigation, further increasing production risks. Livestock production was also adversely affected by shortages of fodder and drinking water. Overall, the combined effects of delayed sowing, water scarcity, and physiological stress are expected to substantially reduce kharif crop productivity during 2026, with small and marginal farmers facing the greatest economic and livelihood challenges due to their limited access to irrigation and financial resources.

Impacts on Farmers' Livelihoods

The widespread drought conditions during 2026 had profound socio-economic consequences for millions of Indian farmers, particularly those dependent on rainfed agriculture. As agriculture supports nearly half of India's workforce, the delayed southwest monsoon, prolonged dry spells, and inadequate soil moisture significantly disrupted crop establishment, reduced farm productivity, and lowered household incomes. Small and marginal farmers, who constitute more than 85% of India's farming community, were the most vulnerable due to limited access to irrigation, quality inputs, institutional credit, and crop insurance. Many were forced to delay sowing, re-sow failed crops, or shift from water-intensive crops such as rice and cotton to drought-tolerant alternatives like millets, pulses, and sorghum, often resulting in higher cultivation costs and reduced economic returns.

The decline in crop production also affected allied sectors, including livestock, dairy farming, and agricultural labor. Reduced fodder availability and water scarcity lowered livestock productivity and milk production, while fewer agricultural operations decreased employment opportunities for rural laborers, prompting seasonal migration to urban areas. Declining groundwater levels and reservoir storage further intensified competition for water among agriculture, domestic, and industrial sectors. Lower production of staple crops increased food prices, threatening food security for economically weaker households. Rising cultivation costs, crop failures, mounting debt, and income uncertainty also caused considerable psychological stress among farmers, highlighting that the 2026 drought was not only an agricultural crisis but also a major socio-economic challenge requiring comprehensive policy support and climate-resilient livelihood strategies.

Government Interventions and Climate-Resilient Adaptation Strategies

The increasing frequency and severity of droughts highlight the need for proactive drought management and climate-resilient agriculture. The Government of India has implemented several

initiatives, including the Pradhan Mantri Fasal Bima Yojana (PMFBY) for crop insurance, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) to promote efficient irrigation, and MGNREGA to generate rural employment and support water conservation infrastructure. Real-time weather forecasting and drought monitoring by the India Meteorological Department (IMD) and research institutions enable timely advisories for improved crop and irrigation management. Farmers are encouraged to adopt drought-tolerant and short-duration crop varieties, diversify cropping systems, and implement water-saving technologies such as drip irrigation, rainwater harvesting, watershed development, and groundwater recharge. Soil moisture conservation practices, including mulching and conservation tillage, further enhance resilience. In the long term, investments in climate-smart agriculture, precision farming, artificial intelligence-based decision support, agricultural research, improved seed systems, and strengthened extension services will be essential for enhancing the sustainability and resilience of Indian agriculture under changing climatic conditions.

Future Perspectives

Climate projections indicate that India is likely to experience more frequent and severe droughts due to rising temperatures and increasing climate variability. Although annual rainfall may remain relatively stable, its uneven distribution and prolonged dry spells will pose significant challenges to agricultural productivity, water resource management, and food security. Strengthening climate resilience through improved drought monitoring, climate-informed agricultural planning, sustainable groundwater management, and the adoption of climate-smart technologies will be essential for ensuring sustainable agricultural development under changing climatic conditions.

Conclusion

The 2026 drought highlighted the increasing vulnerability of Indian agriculture to climate variability, delayed monsoon onset, rainfall deficits, and the strengthening influence of El Niño. These factors disrupted kharif sowing, reduced cultivated area, intensified moisture stress, and adversely affected agricultural productivity, food security, water resources, and the livelihoods of millions of farmers, particularly those dependent on rainfed agriculture. The event underscores the urgent need for climate-resilient agricultural systems through the adoption of drought-tolerant crop varieties, efficient irrigation, soil and water conservation, climate-smart farming, weather-based advisories, strengthened crop insurance, sustainable resource management, and improved institutional support to enhance agricultural resilience and ensure long-term food and livelihood security.

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NANO-ENHANCED CHITOSAN ACETATE CLOTH FILTERS AS A NEXT-GENERATION ECO-FRIENDLY ADSORBENT FOR WASTEWATER TREATMENT

**M. Dhanu Pradeep¹, L. Vinoth Kumar^{2*}, G.Dhivagar¹,
E.K.Devipriya¹, R.Gayathri¹ and S. T. Dhivya Bharathi¹**

¹B.F.Sc Scholar, TNJFU - Dr. MGR. Fisheries College and Research Institute,
Ponneri, Thiruvallur- 601204, Tamil Nadu

²Assistant professor, Department of Fish Processing Technology,
TNJFU - Fisheries College and Research Institute, Thoothukudi-628 008, Tamil Nadu.

*Corresponding Email: vinothkumar@tnfu.ac.in

Abstract

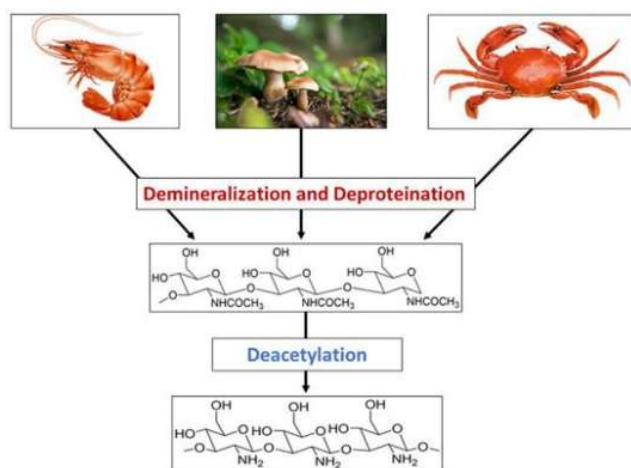
Water pollution is a growing global problem caused by harmful substances released from industries, agriculture, and urban activities. To address this issue, researchers are exploring eco-friendly and cost-effective treatment methods. One promising solution is the use of nano-enhanced chitosan acetate cloth filters. Chitosan, a natural material obtained from shell waste like shrimp and crab, is biodegradable, non-toxic, and highly effective in removing pollutants due to its active binding sites. However, its direct use has some limitations, such as low strength and stability. By modifying chitosan and combining it with nanomaterials, its performance can be greatly improved, offering higher adsorption capacity, better durability, and reusability. When designed in cloth filter form, it becomes easy to handle and suitable for continuous water purification systems. These advanced filters can efficiently remove heavy metals, dyes, and other contaminants, making them a sustainable and practical solution for clean water.

Introduction

Water pollution has become a serious global issue due to rapid industrialization, urbanization, and agricultural activities, which release harmful substances such as heavy metals, dyes, pharmaceuticals, and organic pollutants into water bodies, posing significant risks to both ecosystems and human health. Conventional wastewater treatment methods often face challenges such as high cost, low efficiency in removing trace contaminants, and the generation of secondary pollution. Among these, chitosan, a natural biodegradable and biocompatible polymer, has gained significant attention due to its strong adsorption capacity, attributed to the presence of amino and hydroxyl functional groups that interact effectively with contaminants. However, raw chitosan has certain limitations, including poor mechanical strength, low surface area, and instability under acidic conditions, which restrict its practical applications. To overcome these drawbacks, then modified forms such as chitosan acetate and incorporated nanomaterials to enhance its properties. These nano-enhanced composites exhibit improved adsorption efficiency, greater stability, higher selectivity, and better reusability. In addition, chitosan-based cloth filters offer advantages such as flexibility, ease of handling, and suitability for continuous filtration systems, making them more practical for real-world applications. Therefore, nano-enhanced chitosan acetate cloth filters are emerging as a promising next-generation, eco-friendly, and scalable solution for advanced wastewater treatment.

Sources

Chitosan is derived from chitin, usually obtained from natural sources such as the residues of shrimp, crab and lobster, fungal mycelia and green algae. This biopolymer can also be found in the exoskeletons of insects and fungal cell walls. Chitin content in fungi varies between 19% and 42%, compared to the exoskeleton, where chitin can reach up to 75%. Not all shellfish wastes are good sources of chitin. The blue crab (*Callinectes*) contains 14% of chitin, while oyster and clam shells have chitin content in the range of 4–6%. Chitin content can vary with the proportion of minerals, proteins, and carotenoids, depending on the species, reproductive cycle phase, nutritional status, age, and also the peeling conditions during the processing. Chitosan can be obtained by deacetylation of chitin through enzymatic or alkaline methods



Chitosan as a green adsorbent

Chitosan is a naturally derived biopolymer obtained from chitin, which is abundantly present in the shells of crustaceans such as crabs and shrimp, and it has emerged as an effective green adsorbent for wastewater treatment due to its eco-friendly nature and high efficiency. It is considered a sustainable material because it is biodegradable, non-toxic, and derived from renewable waste resources, thereby supporting environmentally friendly and circular economy practices. The chemical structure of chitosan contains functional groups such as amino (-NH₂) and hydroxyl (-OH), which provide active binding sites for the adsorption of a wide range of pollutants, including heavy metals, dyes, and organic contaminants, through mechanisms like chelation, electrostatic attraction, and hydrogen bonding. Chitosan exhibits high adsorption capacity and can be easily modified into various forms such as beads, membranes, nanoparticles, and composites to enhance its mechanical strength, stability, and efficiency. It is widely used for removing contaminants like lead, copper, nickel, synthetic dyes, and pharmaceutical residues from wastewater. Recent advancements have further improved its performance by combining chitosan with other materials, including nanoparticles and natural fibres, resulting in enhanced adsorption properties. However, chitosan has certain limitations, such as solubility in acidic conditions and relatively low mechanical strength, which can effectively addressed through chemical modifications like cross-linking and grafting.

Modified chitosan in wastewater treatment:

Modified chitosan can be used for a variety of wastewater treatment applications, including coagulation, flocculation, adsorption, and membrane filtration. In coagulation and flocculation

applications, modified chitosan can be used as a coagulant aid to improve the efficiency of traditional coagulants such as alum or ferric chloride. Modified chitosan can also be used as an adsorbent to remove pollutants such as heavy metals, dyes, and organic compounds from wastewater. Modified chitosan plays a significant role in membrane filtration applications by acting as a functional material that enhances membrane performance through surface modification or as a composite component in membrane fabrication. Its incorporation into polymeric membranes improves key properties such as hydrophilicity, permeability, and antifouling behaviour, which are essential for efficient wastewater treatment. The introduction of functional groups like carboxyl, sulfonate, and quaternary ammonium onto the chitosan backbone increases its affinity toward a wide range of contaminants, thereby improving rejection efficiency. As a result, chitosan-based membranes and coatings are capable of effectively removing suspended solids, microorganisms, heavy metals, and emerging pollutants including pharmaceuticals and personal care products.

Nano-enhancement of chitosan-based materials :

These materials transforming natural chitosan into nanoscale forms such as nanoparticles, nanofibers, nanogels, and nanocomposites to significantly improve its physicochemical and functional properties. Chitosan, a biodegradable and biocompatible polymer derived from chitin, contains reactive amino and hydroxyl groups that enable easy modification and nano-structuring. At the nanoscale, these materials exhibit increased surface area, higher reactivity, improved adsorption capacity, and enhanced mechanical strength, making them highly effective for a wide range of applications. Common synthesis methods include ionic gelation, microemulsion, spray drying, and crosslinking with agents like sodium tripolyphosphate, with ionic gelation being widely preferred due to its simplicity and eco-friendly nature. The incorporation of nanotechnology greatly enhances chitosan's performance, particularly in wastewater treatment, where it efficiently removes heavy metals, dyes, and organic pollutants due to its high surface-to-volume ratio and abundant active sites. In the biomedical field, nano-enhanced chitosan serves as an excellent drug delivery system, improving drug stability, bioavailability, and targeted release, while also being used in wound healing, tissue engineering, and antimicrobial applications. Additionally, these materials are gaining importance in agriculture as nano-fertilizers and plant-protection agents, and in the food industry for nanoencapsulation to improve shelf life and nutritional value. Despite challenges such as production cost and scalability, ongoing advancements in green synthesis and nanotechnology are expected to expand its applications, making nano-enhanced chitosan a promising, sustainable material for future environmental, biomedical, and industrial solutions.

Recent advances in chitosan-based wastewater treatment:

These highlight the development of smart and high-performance materials through nanotechnology, functional modification, and hybrid systems. A key innovation is the formation of chitosan-based nanocomposites, where chitosan is combined with materials such as metal oxides, graphene, or polymers to enhance surface area, adsorption capacity, and mechanical strength. These advanced materials show remarkable efficiency in removing a wide range of contaminants, including heavy metals, dyes, pharmaceuticals, and other emerging pollutants. The incorporation of magnetic nanoparticles into chitosan matrices further improves the process by enabling easy separation of the adsorbent from water using an external magnetic field, thereby increasing reusability and operational efficiency. In addition, techniques like cross-linking and surface functionalization help tailor the physicochemical properties of chitosan, improving its stability under varying environmental conditions and enhancing its selectivity for specific pollutants.

Emerging smart technologies, such as stimuli-responsive chitosan hydrogels and nanogels, can adapt to environmental changes like pH, temperature, or ionic strength, allowing controlled and efficient pollutant removal. Moreover, the integration of chitosan-based materials with advanced treatment methods, including membrane filtration and electrochemical systems, has significantly improved treatment performance and scalability. Overall, these innovations reflect a shift toward sustainable, reusable, and intelligent water treatment solutions, positioning modified chitosan as a promising material for modern wastewater management.

Conclusion

The development of nano-enhanced chitosan acetate cloth filters represents a promising and sustainable approach for improving wastewater treatment. Chitosan, derived from natural shell waste such as shrimp and crab, offers an eco-friendly alternative to conventional synthetic materials due to its biodegradable, non-toxic, and renewable nature. However, its natural limitations, including low mechanical strength and stability, can be effectively overcome through chemical modification and nanotechnology. By incorporating nanomaterials and designing the adsorbent in cloth filter form, the efficiency, durability, and reusability of chitosan can be significantly enhanced. These advanced filters demonstrate strong potential for removing heavy metals, dyes, and other harmful pollutants from contaminated water. Overall, nano-enhanced chitosan acetate cloth filters provide a practical, cost-effective, and environmentally friendly solution that supports sustainable water purification and contributes to addressing the growing global challenge of water pollution.

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ORGANIC PEST AND DISEASE MANAGEMENT IN BRINJAL CULTIVATION: A PRACTICAL GUIDE FOR FARMERS

Maimom Soniya Devi^{1*}, Rakesh Yonzon² and Sanjog Chhetri³

¹Department of Plant Protection, College of Horticulture,
Central Agricultural University (Imphal), Birmok, Sikkim, 737134

²Department of Plant Pathology, College of Agriculture (Extended Campus),
Uttar Banga Krishi Viswavidyalaya, Majhian, 733133

³Regional Station, Indian Agriculture Research Institute, Kalimpong, West Bengal, 73430.

*Corresponding Email: maimomsoniya.cau@gmail.com

Introduction

Brinjal, also known as eggplant or aubergine (*Solanum melongena* L.), is one of the most widely cultivated vegetable crops across Asia, Africa, and parts of the Mediterranean region. In India, it is an indispensable vegetable in home kitchens and an important source of income for millions of small and marginal farmers. Its adaptability to diverse climatic conditions, long harvesting period, and high market demand make it one of the most profitable vegetable crops. Rich in dietary fibre, vitamins, minerals, and antioxidants, brinjal also contributes significantly to nutritional security. Despite its popularity, brinjal is among the most pest- and disease-prone vegetable crops. From the nursery stage to the final harvest, the crop is constantly threatened by insects such as the shoot and fruit borer, aphids, jassids, whiteflies, thrips, and mites, as well as fungal and bacterial diseases including Phomopsis blight, Fusarium wilt, damping-off, and bacterial wilt. In severe cases, pests such as the shoot and fruit borer alone can damage nearly the entire crop if left unmanaged.

For decades, chemical pesticides have been the primary tool for controlling these problems. However, repeated and indiscriminate pesticide use has created new challenges. Many pests have developed resistance to commonly used insecticides, beneficial insects have been eliminated, secondary pest outbreaks have become more frequent, and pesticide residues have entered the food chain. Because brinjal fruits are harvested repeatedly over several months, farmers often find it difficult to maintain the recommended waiting period after spraying, increasing the risk of pesticide residues reaching consumers. Growing awareness about food safety, environmental protection, and sustainable agriculture has renewed interest in organic pest and disease management. Rather than relying on a single solution, organic farming combines healthy soils, preventive cultural practices, biological control agents, botanical pesticides, and regular field monitoring to maintain pest populations below damaging levels. This integrated approach not only protects the crop but also conserves biodiversity, improves soil health, and produces safe, residue-free vegetables.

Why Brinjal Is Highly Susceptible to Pests and Diseases

Brinjal belongs to the Solanaceae family, which also includes tomato, chilli, potato, and tobacco. These crops share many common insect pests and diseases. As a result, continuous cultivation of solanaceous vegetables in the same field encourages the build-up of pest populations and disease-causing organisms. Another reason for the crop's vulnerability is its long duration in the field. Unlike many vegetables that are harvested once, brinjal produces fruits continuously for

four to six months. This extended cropping period allows several generations of insect pests to multiply and provides ample opportunity for soil-borne pathogens to spread. Furthermore, the crop's succulent shoots and tender fruits are highly attractive to boring insects, while its dense canopy often creates a humid microclimate favourable for fungal diseases.

Understanding these biological characteristics is essential because successful organic management depends largely on prevention rather than cure.

Major Insect Pests of Brinjal

Shoot and Fruit Borer

The brinjal shoot and fruit borer (*Leucinodes orbonalis*) is undoubtedly the most destructive insect pest of the crop throughout South and Southeast Asia. Adult moths lay eggs on tender shoots, flower buds, and developing fruits. Soon after hatching, the larvae bore directly into plant tissues where they remain protected from external sprays. Infested shoots wilt and dry, producing the characteristic "dead heart" symptom. During fruiting, larvae tunnel into developing fruits, leaving small entry holes that soon become plugged with excreta. Although external damage may appear limited, the fruits become unmarketable and unsuitable for consumption. Since the larvae remain hidden inside shoots and fruits for most of their life cycle, preventive measures are much more effective than curative sprays.

Sap-Sucking Insects

Several sap-feeding insects attack brinjal throughout its growth. Aphids colonize young shoots and leaves, extracting plant sap and causing leaf curling, yellowing, and stunted growth. Whiteflies weaken plants by sucking sap and secreting honeydew, which encourages black sooty mould growth. More importantly, they transmit viral diseases that severely reduce crop productivity. Jassids feed along leaf margins, causing the characteristic "hopper burn," where leaves curl upward, turn yellow, and eventually dry. Thrips and mites also become problematic during hot, dry weather, reducing photosynthesis by damaging leaf tissues. Although individually these insects may appear insignificant, together they weaken plants, reduce fruit yield, and increase susceptibility to diseases.

Major Diseases of Brinjal

Phomopsis Blight and Fruit Rot

Phomopsis blight is one of the most destructive fungal diseases affecting brinjal. It attacks seedlings, leaves, stems, and fruits, making it capable of causing heavy yield losses throughout the crop cycle. The disease begins as small greyish-brown leaf spots with dark margins. As infection progresses, lesions enlarge and spread to stems and fruits. Infected fruits develop sunken brown patches that gradually rot, making them unfit for marketing or consumption.

Bacterial Wilt

Bacterial wilt, caused by *Ralstonia solanacearum*, is among the most feared diseases of brinjal in warm and humid regions. Affected plants wilt suddenly despite adequate soil moisture. Initially, the leaves remain green, but the entire plant eventually collapses. Cutting the stem often reveals brown vascular tissues, and a milky bacterial ooze may be seen under moist conditions. Because the bacterium survives in soil and irrigation water for long periods, the disease becomes difficult to manage once established.

Fusarium Wilt

Unlike bacterial wilt, Fusarium wilt develops gradually. Lower leaves begin to yellow before wilting spreads upward through the plant. Brown discoloration of the vascular tissue is often visible

inside the stem. The fungus survives in soil for several years, making crop rotation and soil health particularly important.

Damping-off

Damping-off mainly affects seedlings in the nursery. Young seedlings collapse at the soil surface due to infection by soil-borne fungi such as *Pythium* and *Rhizoctonia*. Poor drainage, overcrowding, and excessive watering greatly increase disease incidence.

Building an Organic Management Programme

Organic pest and disease management does not rely on replacing one pesticide with another. Instead, it combines several complementary practices that strengthen the crop while reducing pest populations naturally.

Begin with Healthy Soil

Healthy soil is the foundation of healthy plants. Incorporating well-decomposed farmyard manure, vermicompost, compost, and neem cake improves soil fertility while encouraging beneficial microorganisms that naturally suppress disease-causing fungi and bacteria. Crop rotation is equally important. Avoid growing brinjal or other solanaceous crops in the same field year after year. Rotating with cereals or legumes breaks the life cycles of many soil-borne pathogens. Where feasible, soil solarization during the hottest months can significantly reduce populations of harmful fungi, bacteria, nematodes, and weed seeds.

Raise Healthy Seedlings

Good crop health begins in the nursery. Use certified disease-free seed whenever possible. Raise seedlings on well-drained raised beds or in sterilized nursery trays. Avoid excessive irrigation and overcrowding, which favour damping-off. Treating seeds with beneficial fungi such as *Trichoderma* before sowing provides early protection against several soil-borne diseases. Root dipping seedlings in *Trichoderma* or *Pseudomonas fluorescens* suspension before transplanting further improves disease resistance.

Maintain Good Field Hygiene

Regular field sanitation is one of the simplest and most effective pest management practices. Inspect plants every week. Remove wilted shoots attacked by the shoot and fruit borer before larvae complete their development. Similarly, collect and destroy damaged fruits instead of leaving them in the field, where they become breeding sites for future infestations. After harvest, remove and destroy crop residues to reduce the carry-over of pests and pathogens into the next season.

Use Proper Crop Spacing

Adequate spacing allows sunlight and air to circulate freely within the crop canopy. Better air movement reduces humidity, discouraging fungal diseases while making pest scouting much easier.

Encourage Biodiversity

A diverse farm supports a healthy ecosystem. Intercropping brinjal with coriander, marigold, fenugreek, onion, or legumes helps attract beneficial insects while confusing pests searching for host plants. Flowering border crops provide nectar and pollen for natural enemies such as parasitic wasps and hoverflies. Installing simple bird perches encourages insect-eating birds that feed on caterpillars and other pests throughout the season.

Mechanical and Physical Control

Several inexpensive physical methods can substantially reduce pest populations. Pheromone traps are highly effective for monitoring and mass trapping male shoot and fruit borer moths. Installing traps about two weeks after transplanting helps reduce mating and provides early warning of increasing pest populations. Yellow sticky traps effectively attract whiteflies, aphids, and jassids, while blue sticky traps capture thrips. Fine nylon netting over nursery beds protects young seedlings from insect vectors that spread viral diseases. Regular hand collection of insect egg masses, larvae, and diseased plant parts remains one of the most economical practices for small farms.

Botanical Pesticides

Among botanical pesticides, neem remains the most trusted and widely used option in organic farming. Neem oil, neem seed kernel extract, and commercial azadirachtin formulations interfere with insect feeding, growth, moulting, and reproduction. Unlike synthetic pesticides, neem products are relatively safe for beneficial insects, pollinators, farm workers, and consumers when used correctly. Regular spraying of neem oil or 5 percent neem seed kernel extract at weekly intervals provides effective suppression of shoot and fruit borer, aphids, whiteflies, jassids, thrips, mites, and several other insect pests. Because neem breaks down rapidly in sunlight, repeated applications are necessary during periods of heavy pest pressure. Garlic-chilli extract and pongamia oil can also be used as supplementary botanical sprays against sucking insects.

Biological Control: Nature's Own Pest Managers

Beneficial microorganisms and insects play a central role in organic pest management. *Trichoderma* species suppress many soil-borne fungi responsible for damping-off, Fusarium wilt, and Phomopsis blight while stimulating root growth and plant immunity. *Pseudomonas fluorescens* protects roots from bacterial and fungal pathogens while promoting vigorous plant growth. *Bacillus thuringiensis* (Bt) is highly effective against young caterpillars of the shoot and fruit borer. Once ingested, the bacterium kills larvae without affecting humans, livestock, pollinators, or natural enemies. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* infect and kill many insect pests under favourable environmental conditions. Egg parasitoids like *Trichogramma* attack the eggs of the shoot and fruit borer before larvae hatch, preventing damage before it begins. Equally important is conserving naturally occurring predators such as ladybird beetles, lacewings, spiders, hoverflies, praying mantises, and parasitic wasps by avoiding unnecessary pesticide use.

Organic Nutrient Management for Stronger Plants

Healthy plants are naturally more resistant to pests and diseases. Apply 20–25 tonnes of well-decomposed farmyard manure per hectare before planting, supplemented with vermicompost, neem cake, or enriched compost where available. Biofertilizers containing *Azotobacter*, phosphate-solubilizing bacteria, and mycorrhizal fungi improve nutrient uptake and root development. Traditional organic formulations such as Jeevamrut and Panchagavya stimulate beneficial microbial activity and enhance plant vigour. Mulching with crop residues or straw conserves soil moisture, suppresses weeds, moderates soil temperature, and creates favourable conditions for soil organisms. Balanced nutrition is essential because excessive nitrogen encourages lush, succulent growth that attracts aphids, jassids, and other sap-sucking insects.

Practical Organic Management Calendar

Before planting: Rotate crops, prepare fertile soil with compost and neem cake, solarize nursery beds if possible, and treat seeds with *Trichoderma*.

Nursery stage: Raise seedlings on well-drained beds under insect-proof netting and avoid excessive irrigation.

Two weeks after transplanting: Install pheromone traps, yellow sticky traps, and bird perches. Begin weekly crop inspection.

Vegetative stage: Remove damaged shoots regularly. Spray neem-based formulations when early pest activity is observed.

Flowering stage: Continue field sanitation, release biological control agents where available, and monitor for whiteflies and aphids.

Fruiting stage: Harvest regularly, destroy damaged fruits, apply *Bacillus thuringiensis* against young caterpillars if needed, and maintain adequate irrigation and balanced nutrition.

After harvest: Remove all crop residues and plan crop rotation for the following season.

Why an Integrated Organic Approach Works

Experience from farmers and agricultural research consistently shows that no single organic practice provides complete protection against every pest or disease. However, when healthy soil, resistant varieties, crop rotation, field sanitation, pheromone traps, sticky traps, botanical pesticides, and biological control agents are combined, pest populations remain well below damaging levels.

Unlike chemical-intensive systems, organic farming conserves beneficial insects, improves soil fertility, reduces production costs over time, and minimizes environmental pollution. Consumers increasingly prefer vegetables grown with little or no pesticide residue, creating opportunities for farmers to obtain premium prices in local and urban markets.

Conclusion

Brinjal may always remain one of the most challenging vegetable crops to protect, but it does not require constant dependence on synthetic pesticides. Successful organic pest and disease management is built on prevention rather than cure. Healthy soils, vigorous seedlings, crop rotation, careful field sanitation, regular monitoring, botanical pesticides such as neem, and biological control agents including *Trichoderma*, *Pseudomonas fluorescens*, *Bacillus thuringiensis*, *Beauveria bassiana*, and *Trichogramma* together form a resilient production system that protects both crops and the environment.

For farmers, adopting this integrated organic approach means more than reducing pesticide use. It means healthier soils, stronger plants, lower production costs over time, safer food for consumers, greater biodiversity on the farm, and improved long-term profitability. As demand for residue-free vegetables continues to grow, organic pest and disease management offers a practical pathway toward sustainable, productive, and environmentally responsible brinjal cultivation.

EFFICIENT PLANNING OF RICE-MANAGEMENT EXPERIMENTS USING FRACTIONAL FACTORIAL DESIGNS

**Vankudoth Kumar^{1,2*}, Sukanta Dash², Med Ram Verma²,
Anil Kumar³, Sunil Kumar Yadav² and Prabhakar Verma^{1,2}**

¹The Graduate School, ICAR-IARI, New Delhi-110012

²ICAR-IASRI, Pusa, New Delhi-110012

³Krishi Bhavan, ICAR, New Delhi-110012

*Corresponding Email: kumarvankudoth51@gmail.com

Agricultural experiments involving several management factors often require a very large number of treatment combinations, making complete factorial experimentation difficult in terms of land, labour, time, and cost. Three-level fractional factorial designs provide a practical alternative by selecting a scientifically structured subset of treatments while retaining useful information on important factor effects. This article explains the application of fractional factorial designs through the `lfebd3` package and illustrates their use in a rice-establishment experiment involving variety, nitrogen dose, irrigation schedule, transplanting age, and weed management. A complete five-factor experiment requires 243 treatment combinations, whereas fractionation can reduce the experiment to 81 or even 27 runs. The approach is particularly useful for preliminary screening of influential crop-management practices. However, because some effects may be aliased, the defining contrasts and confounding structure must be carefully examined before selecting and interpreting the design.

Keywords: Three-level factorial design; fractional factorial; rice crop management; aliasing; R package.

Introduction

Crop performance is rarely controlled by a single practice. Variety, nutrient supply, water management, planting method, seedling age, and weed control may all contribute to yield. Their effects may also depend on one another. For instance, the benefit of additional nitrogen may change with irrigation regime, while a planting method may perform differently across varieties.

When each factor is studied at three settings, the number of combinations increases as 3^n , where n denotes the number of factors. Five factors require 243 treatments and six factors require 729 treatments before replication. Such experiments may be statistically attractive but operationally unrealistic. Fractionation provides a planned reduction rather than an arbitrary removal of treatments (Xu, 2003).

Using the `lfebd3` Package

The verified fractional-design generator in the `lfebd3` package is `lfebd3.fr(n, r)`. Here, n is the number of three-level factors and r is the degree of fractionation. The returned object contains the selected run table, its numeric design matrix, the defining contrasts, and a summary of confounding involving main effects and two-factor interactions (Kumar *et al.*, 2026).

```
library(lfebd3)
fraction <- lfebd3.fr(n = 5, r = 2)
fraction$design
fraction$defining_contrasts
```


For $n = 5$ and $r = 2$, the number of runs is $3^{(5-2)} = 27$. Before choosing this smaller fraction, the defining contrasts and confounding summary should be examined to confirm that effects of primary scientific interest are not grouped in an unacceptable way.

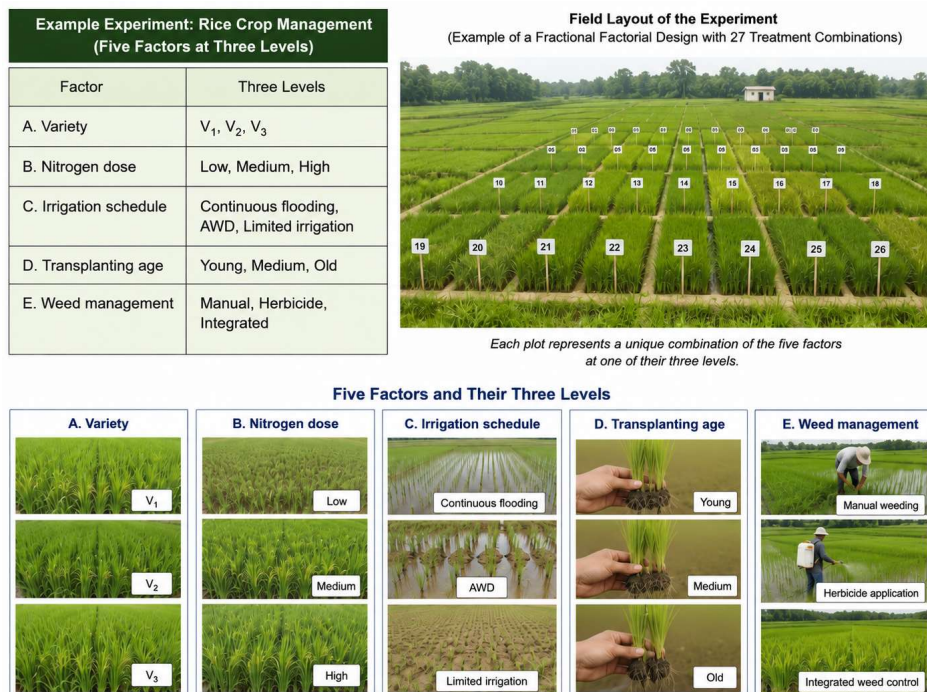
Generation and diagnostic analysis can also be combined in one call. For a 27-run fraction treated as one block, `block_size` is set to 27. Exact or fast diagnostics may then be selected according to the size and purpose of the design.

```
analysis <- lfebd3_analyze(  
  type = "lfebd3.fr",  
  n = 5, r = 2,  
  block_size = 27,  
  show_design = FALSE,  
  run_analysis = TRUE,  
  fast = FALSE)  
print(analysis)
```

The combined output gives the generated design, block representation, design-characteristic results, and the fractional confounding information. This provides a reproducible record of how the treatment set was obtained and assessed (Dash *et al.*, 2025; Yadav *et al.*, 2026).

Illustration: Rice establishment trial

Consider a preliminary rice experiment intended to identify the crop-management practices that deserve detailed testing in a later season. Five factors are selected, and each is examined at three practically meaningful levels. The complete experiment contains 243 treatment combinations. A one-third fraction uses 81 plots, whereas a one-ninth fraction uses only 27 plots. The 27-run option may be suitable for initial screening when the immediate goal is to identify large effects rather than to estimate every interaction independently.



Conclusion

Three-level fractional factorial designs offer a practical route for studying several rice-management practices when a complete experiment is too large. For five factors, the run size can be reduced from 243 to 81 or 27, producing substantial savings in land, inputs, labour and observation effort. The *lfebd3* package makes the construction transparent by providing the selected treatments, defining contrasts and confounding information. The approach is most effective when it is used as a carefully checked screening tool, followed by a focused and replicated confirmation trial. In this way, researchers can obtain useful evidence from limited resources without treating economy as a substitute for sound experimental planning.

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NATURAL FARMING IN HORTICULTURAL SYSTEMS: PRINCIPLES, PRACTICES AND PROSPECTS FOR SUSTAINABLE TRANSFORMATION

Eashwar V

IV Year B.Sc. (Hons.) Horticulture, TNAU,
Horticultural College and Research Institute, Periyakulam - 625 604
Corresponding Email: eashwar496@gmail.com

Abstract

Conventional horticulture leans heavily on synthetic chemicals, and that's been rough on the land - soil health has taken a hit, water systems get polluted, and there are more pesticides showing up in our fruits and veggies. Natural farming tries to fix this. It's all about skipping the chemicals and working closer to nature, especially in approaches like Zero Budget Natural Farming (ZBNF) and Bharatiya Prakritik Krishi Paddhati (BPKP). These methods use native bioinoculants, focus on smart water management, and mix up the crops, so farmers spend less on inputs but end up with better produce and healthier ecosystems.

Keywords: Natural farming, ZBNF, BPKP, Jeevamrit, Beejamrit, sustainable horticulture, agroecology

Introduction

The Green Revolution transformed Indian agriculture, bringing huge jumps in productivity. But it also locked farmers into a system heavily reliant on chemicals and the long-term fallout is impossible to ignore now. Over the years, soil lost its life, groundwater got tainted, and the fresh fruits and veggies people eat every day often come with unsafe levels of pesticide residue. India's the world's second-largest vegetable producer, so the stakes are even higher big problems, but also big possibilities if something changes (Noopur *et al.*, 2025). Horticulture really sits at the center of this challenge. It uses tons of agrochemicals, and since the food usually goes straight to the consumer, there's no chance for processing to remove those residues.

Concept and evaluation of Natural farming

Natural farming strips agriculture down to basics no chemicals, just working with nature's own systems. The roots go back to Masanobu Fukuoka's idea of letting nature do its thing, with as little interference as possible. In India, this approach has taken shape as Zero Budget Natural Farming (ZBNF), thanks to Dr. Subhash Palekar. The main idea? Farmers depend entirely on what they have on hand, especially biological inputs from local cattle no need to buy stuff from outside. To really push this forward, the Indian government set up the Bharatiya Prakritik Krishi Paddhati (BPKP). It falls under the wider Paramparagat Krishi Vikas Yojana (PKVY) and helps farmers switch over with things like Bio-Input Resource Centres, hands-on training, and even some financial support. Now, don't mix this up with organic farming. Organic farms might still buy certified inputs, which means spending money and depending on the market. Natural farming, on the other hand, demands you make everything right there on the farm. That's what makes it practical for small farmers they don't have to keep shelling out cash or rely on anyone else (Kumar *et al.*, 2019).

Key inputs, Indigenous formulation and Soil Health Management

Natural farming brings soil back to life by encouraging a healthy community of microbes, instead of just pouring on chemical fertilizers. It relies mainly on three homemade solutions. First, there's Beejamrit - a mix of cow dung and urine used to coat seeds with friendly microbes. This layer helps shield seeds from diseases and boosts how well they sprout. Next up is Jeevamrit - a lively blend fermented for two days out of cow dung, urine, jaggery, pulse flour, and a bit of soil. It wakes up the soil's natural organisms, helping nutrients cycle and keeping plant diseases in check. Just a single litre holds around 500 million helpful microorganisms. Then there's Ghanjeevamrit, which is pretty much Jeevamrit but in solid form, so it lasts longer and goes into the soil during field prep, feeding microbes right where roots grow. These three together steadily rebuild the soil's richness, activity, and structure - no outside chemicals or expensive inputs required (Noopur *et al.*, 2025).

Water Management, Mulching and Microclimate Regulations

Natural farming treats irrigation in a whole new way. It leans on two main ideas. First up is Whapasa. That's just when the soil has the perfect mix of air and water vapor inside. Roots love it when they get that balance, they soak up water and nutrients way more efficiently. So, to keep Whapasa going, farmers water their fields more often, but with a lot less water each time. That simple switch cuts water use by about 30–50% compared to regular methods. The second big thing is Achhadana—basically, mulching. It's pretty straightforward: just cover the soil with crop leftovers or living mulch plants. That protects the soil, keeps it cool, stops weeds from spreading, and locks in moisture. Plus, all that plant material slowly breaks down and adds organic matter right back into the earth. In orchards, farmers often use legume plants as live mulch. It's a win-win—they actually fix nitrogen in the soil, so you end up with stronger, healthier trees and richer soil. You don't just save water—your whole farm gets a boost (Noopur *et al.*, 2025).

Crop diversifications and Systems Approaches

Natural farming flips the script on monoculture. Instead of growing just one thing, farmers carefully mix grains, beans, veggies, and fruit trees all on the same land. It's not just pretty to look at—it's smart. This kind of planning gives the farm some built-in safety nets. If one crop flops or the market tanks, the others pick up the slack and help keep money coming in. Walk through an orchard like this and you'll spot vegetables tucked between rows of young fruit trees. Legumes soak nitrogen right into the soil, while aromatic or medicinal plants help fight off pests, no chemicals needed. The whole setup works a lot like a natural forest—everything playing its part. And it isn't just theory. Researchers like Chandel and colleagues (2021) say this kind of system actually makes the soil richer with every new planting.

Ecological Pest and Disease Management

Natural farming doesn't try to wipe out pests with chemicals. Instead, it keeps pests under control so they don't cause any real harm. The trick is using things like neem-based mixes, garlic, chili, cow urine, and other natural ingredients - Neemastra and Brahmastra are two main ones. These formulas work in a few ways: their smell drives bugs away, they break down the bugs' cuticles on contact, and they block the growth of harmful fungi. If you're dealing with a stubborn caterpillar outbreak, Agniastra with extra chili and tobacco does the heavy lifting. What's great is these mixtures don't hang around on the crops; they break down fast, so you won't find any residue when you harvest. And most importantly, pollinators like bees essential for crops such as mangoes, apples, guavas, and strawberries aren't hit by the side effects you'd see with conventional pesticides (Noopur *et al.*, 2025).

Crop-wise applications

Natural farming really works across all kinds of horticulture. Apple orchards in Himachal Pradesh managed with ZBNF are seeing stronger fruit, better color, fresher taste, and longer shelf life compared to those grown with chemicals (Chandel *et al.*, 2021). Veggie growers in Uttarakhand and Himachal Pradesh tried multi-crop setups like tomato, capsicum, and french bean together, or pea and cauliflower—and found that, even though the yields dipped a bit at first, the produce was higher quality. You get more soluble solids, higher ascorbic acid, and everything stays fresh longer. Spice crops are thriving too. When turmeric is grown with bananas or coconuts, it delivers good rhizome yields and packs more curcumin. And for plantation crops like arecanut, coconut and coffee- which already have layered canopies - they're basically built for switching to natural farming.

Economic viability and Market potential

Cutting out purchased chemical inputs usually 40–70% of variable costs in intensive horticulture gives natural farmers quick financial relief. In Himachal Pradesh, for example, apple growers have slashed input costs by about 56%. Some vegetable farmers have seen savings as high as 90%. During the first one to three seasons of switching over, savings are smaller (around 10–25%), but farmers usually see their net income match or even top what they made before, since they're spending less even if their revenue dips. Plus, once their produce is certified as natural, they can sell it for 20–60% more than regular crops in city markets. There's a steady rise in demand for this kind of food health-focused shoppers and export buyers both want residue-free, certified crops.

Environmental impact, Challenges and future prospects

Natural farming systems actually soak up more carbon than they release. When farmers stop using synthetic nitrogen fertilizers and rebuild the organic matter in their soil, the land holds onto more carbon and releases less nitrous oxide - a greenhouse gas. You can actually see soil carbon levels improve within five to seven years after switching to these practices. Plus, using Whapasa-based irrigation basically managing water in a way that keeps both air and moisture in the soil helps farmers use water more efficiently, which is a big win in areas where water is scarce. But there are some real roadblocks. The biggest one is at the farm level: most farmers don't know enough about the timing and prep of biological inputs, how to properly schedule irrigation, or how to design diverse cropping systems. Extension services (the people and systems that usually help spread this kind of knowledge) haven't caught up yet. Then there's the way markets work natural, premium produce doesn't always fetch better prices, especially for small farmers in remote places. Part of the problem is there's no cheap, reliable way to certify that food as "natural," so farmers can't always prove it's worth more. Moving forward, real progress depends on a few key things: actually setting up 10,000 Bio-Input Resource Centres so farmers have what they need, making sure Farmer Producer Organizations get stronger so they can move natural produce through the supply chain, and investing in field research tailored to different crops and regions across India (Noopur *et al.*, 2025). That's what it'll take to scale natural farming for real.

Conclusion

Natural farming offers India's horticulture sector a real chance to change for the better. It rebuilds healthy soil, cuts down on expensive inputs, boosts crop quality, and helps the environment, all at the same time. Of course, making this shift isn't quick or easy farmers need time, support from institutions, and fair ways to sell what they grow. Still, with growing policy support, clear results from the field, and people wanting healthier food, natural farming stands out as a strong way forward for Indian horticulture.

Summary

Natural farming skips the chemicals and gives growers a more eco-friendly way to garden. Think indigenous bioinoculants like Beejamrit, Jeevamrit, and Ghanjeevamrit, plus smart water practices like Whapasa and Achhadana. Farmers mix things up with crop diversity and fight pests with natural botanicals. In India, people have tested these methods on fruits, veggies, spices, and plantation crops. The results are pretty clear: costs go down, soil gets healthier, produce looks and tastes better, and farmers actually earn more. When the right policies, strong institutions, and better market connections come together, natural farming has the power to reshape Indian horticulture.

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**AGRICULTURE IN NORTH AND SOUTH 24 PARGANAS
DISTRICTS OF WEST BENGAL, INDIA****P. Basuchaudhuri**

Formerly at Indian Council of Agricultural Research, New Delhi, India

Corresponding Email: basuchaudhurip@gmail.com**Summary**

North and South Parganas lands are good fertile lands of West Bengal with high productive potentiality. But hot humid climate with often flash flood threat and subsequent occurrence make the situation grief specially in monsoon thus creating sometimes crop damage, failure and management difficult. Presently, number of varieties were evolved to cope with the situation and number of management practices are being undertaken by farmers, as recommended by Agricultural Scientists for management of water, land, nutrition and pest management and also replanting. But availability of quality seeds remain to be a crucial factor for increased productivity.

INTRODUCTION AND DESCRIPTION

North and South 24 Parganas is the most recent deposits of silt carried down the stream of the Ganges and its tributaries creating initially large number of deltas currently known as plain lands. This area is mainly on the eastern side of the river Vagirathi a branch of the Ganges divided at Farraka of Murshidabad district of West Bengal. Vagirathi reaches Bay of Bengal flowing by the side of Kolkata/Calcutta. The agriculture and Aquaculture of these area flourished in humid hot climatic condition for more than 1000 years, such as different types of rice including poprice varieties. Possibly the fibre crops were also grown luxuriantly in these area such as Cotton and Jute, however, presently Jute is grown. Still rice and Jute cultivation is main economy of the agriculture apart from aquaculture. Some 500 years ago, mangrove forest and forest areas were noticed in 80 percent of the area with villages distributed scatterly in places specially along the river and its tributaries. At present only mangrove forest is visualized in the deltas and coastal area of estuaries as reduced Sundarban.

The soil of this area is known as new alluvium soil consisting of 80 percent of silt and clay having High Water Holding Capacity creating muds, low in organics, high in plant minerals like sodium, potassium, magnesium, calcium, aluminium etc. Because of capillary pores moisture is retained but aeration is restricted in the root zone. Microbial activities is medium as organic substrates are limited but algae and similar bacteria when decomposed provide organics. In cultivated land main source of organics is decomposed cattle and poultry farm waste. So, it is low in nitrogen and phosphorus. In some areas arsenic minerals are deposited in high amount under earth surface crust causing underground water arsenic toxic. In general zinc is low and because of high cultivation performance zinc management is necessary with soil test. Soil salinity in coastal plain is another aspect which comes in fore to substantiate the productivity. Salinity disintegrates the soil particles affecting soil structural property. Gypsum application appears to be important in the cultivation but ammonium sulphate should not be applied as nitrogen fertilizer. Abundant of calcium may replace sodium during mass flow of water and transport of nutrients in to plants preferentially than sodium so that plants are less under salinity stress. Salinity tolerant varieties are also available.

Topography of the land in this area is known as plain land. However, it can be divided as Homestead land, shallow low land and low land other than aquaculture land. Earlier in paddy cultivation continuous flooding of land was practiced even in modern dwarf rice varieties but now –a-days to reduce gas emission drying and wetting is maintained. However, this is not applicable for lowlying situation during monsoon season. In nearby delta areas submerged rice is grown. Annual flash flood and heavy downpour sometimes causes inundation of cultivated areas causing damage to the standing crop. In patches of land boro rice is practised by farmers with deep tubewell water irrigation during winter.

Homestead Land: With the time and urbanization these land gradually increased. Main reason is population increase as well as migration of people from rural areas because of employment opportunities. In the sequence, there are a considerable homestead land still in rural areas. In these lands vegetables and orchards plants are grown like guava, mango, litchi, jackfruit, bananas, others and all types of vegetables through out the year. This amounts to 10 percent of total cultivable area. These aerable soils are mostly fertile with proper drainage facilities. It is known that income is achieved from these lands. These lands are mostly distributed in North 24 Parganas viz. Barasat, Bangaon Blocks and in South 24 Parganas like Sonarpur, Baruipur, Kalyanpur areas. It may be mentioned that in winter the Bangaon area is producing high quality of peas covering large areas which generate high income to the farmers. On the other hand Baruipur-Kalyanpur area is famous for guava and litchi and providing good income to farmers. However, costly guava varieties like Red guava may be cultivated to some extent. In small area of North 24 Parganas adjacent to Nadia is also known for flower cultivation.

Shallow Low Land: These are the major land areas in North and South 24 Parganas districts of West Bengal having sufficient rainfall during the monsoon period. In some areas High Yielding rice varieties are being grown viz. Swarna, Swarna-Mashuri, Mashuri are grown now-a-days. But major emphasis has been given on transplanting of jute in August with Sub1 variety. Before rice, Jute is grown in large areas of North 24 Parganas bordering Nadia and small areas in South 24 Pargana. Thus jute is also an important cash crop. Apart from these rice varieties minor varieties, Rupsal, Dudhsar varieties are grown because of its popularity. In some areas Gobindabhog variety is also grown. But this is mostly mixed with other type rice seeds hence a rigorous screening after harvest as well as during management is necessary. Otherwise, export may be affected. After harvest of rice generally, Toria sarson is cultivated by ploughing the land or seeds are put in standing rice field when the soil is moist as a rabi crop. However, Rai sarson is also grown in rice fallow where irrigation is available. In some places lentil is being cultivated but mostly goes under vegetable cultivation viz. radish, turnip, beets, carrot even cabbage and cauliflower. It may be mentioned that leafy vegetables including coriander, are grown. Apart from all these some areas are used for Alocasia during rainy season.

Low Land: Lowlands are an important part of cultivated area considered as monocropped. Generally 150 days rice is grown in these lands mainly with the varieties Tilakkachari, Sabita, Sabitri, Mega group of varieties evolved by inducing Sub1 gene in a group of high yielding 150 days local varieties in these lowlying areas. These areas are sometimes affected by flash flood at different stages of growth. So, it gets submerged for 2-3 weeks. After rice a portion of these is cultivated with boro rice. However, vegetables like cucurbits are grown on bunds in these areas. In coastal area rice varieties developed by Central Soil Salinity Research Station, Canning like Canning7, Amal Mana and Bidhan2.

Conclusion: Because of high hot humid climate and storm wind with fish flood the agriculture is vulnerable mostly in North and South 24 Parganas, West Bengal. On the other hand agriculture scenario is quite encouraging round the year. Shallow low land management is of immense importance with time to time soil health management with addition of FYM for optimizing production in respect of potential production capacity.

NUTRI-GARDEN: GROWING NUTRITION AT THE DOORSTEP FOR A HUNGER-FREE INDIA

Myakala Rajesh Kumar¹ and Rajputth Raghuvaran Singh²

¹Young Professional –I, Krishi vigyan Kendra, Palem 509215, Nagarkurnool District, Telangana

²Young Professional –II, Krishi vigyan Kendra, Palem 509215, Nagarkurnool District, Telangana

*Corresponding Email: rajeshraju261999@gmail.com

Abstract

India continues to face the challenge of ‘hidden hunger’ despite achieving food grain self-sufficiency. Micronutrient deficiencies, poor dietary diversity, and rising food costs have made household nutrition insecure, especially in rural and peri-urban areas. The Nutri-Garden, or kitchen garden, is a proven, low-cost model that enables families to grow a variety of vegetables, fruits, and leafy greens in small spaces. By utilizing just 1000–1300 sq.ft of homestead land, a family can produce fresh, safe, and nutritious food throughout the year. Nutri-Gardens not only improve dietary intake and reduce expenditure but also empower women, promote sustainable agriculture, and strengthen community resilience. Successful models from Telangana and other states demonstrate that scaling kitchen gardens through institutional support and policy integration can be a key pathway to achieving nutrition security and the goal of a hunger-free India.

Keywords: Nutri-Garden, Kitchen Garden, Hidden Hunger, Nutrition Security, Sustainable Agriculture, Women Empowerment

Introduction: Food security means more than just having enough calories. It means having access to diverse, safe, and nutritious food at all times. India produces surplus food grains, yet millions suffer from malnutrition. According to national surveys, more than 50% of women and children are anemic, and the intake of fruits and vegetables is far below recommended levels. This gap is called ‘hidden hunger’ because people may eat enough food but still lack essential vitamins and minerals.

Two major factors are driving this problem. First, market prices of vegetables and fruits are rising, making them unaffordable for low-income families. Second, urbanization and changing lifestyles have reduced the space and time available for growing food at home. In this context, the Nutri-Garden model offers a practical solution. A Nutri-Garden is a small plot around the house where families grow vegetables, greens, fruits, and herbs for daily use. It brings nutrition to the doorstep, cuts dependence on markets, and ensures food safety. With climate change and population growth putting pressure on food systems, decentralized models like kitchen gardens are no longer optional — they are essential.

Concept and Components of Nutri-Gardena: Nutri-Garden is designed to provide year-round vegetables for a family of 4–5 members. An area of 1000–1300 sq.ft is sufficient. The garden is planned to include early, medium, and late-duration crops so that harvest is continuous.

Design Models:

- **Raised Bed Model:** 1-meter-wide beds with 30cm drainage channels. Ideal for rainy areas to avoid waterlogging.

- **Pit Method:** 2x2x2 ft pits filled with compost. Suitable for dry regions and roof-tops.
- **Vertical and Container Gardening:** Used in urban homes with limited space. Old buckets, tyres, and bottles can be reused.

Crop Selection:

A well-planned Nutri-Garden includes:

- Leafy greens: Spinach, amaranthus, fenugreek, coriander
- Vegetables: Brinjal, okra, tomato, chillies, gourds
- Root vegetables: Carrot, radish, beetroot
- Fruits: Papaya, banana, drumstick, guava
- Medicinal plants: Tulsi, curry leaf, mint
- Others: Pulses on bunds, and backyard poultry for eggs

Integration of composting units and rainwater harvesting makes the system self-sustaining.



Fig 1. Nutri-Garden design showing vegetables, fruits

Importance of Nutri-Gardens for Nutrition Security

Combating Hidden Hunger Daily consumption of fresh vegetables from Nutri-Gardens directly increases intake of iron, vitamin A, vitamin C, and folate. This helps reduce anemia and vitamin deficiencies among women and children.

Economic Benefits A family can save Rs. 800–1200 per month on vegetable purchases. Surplus produce can be sold in local markets or exchanged within the community, creating a small income stream.

Food Safety and Quality Home-grown produce is free from harmful pesticides and chemicals. Families have full control over inputs, ensuring safe food for children and elderly members.

Climate Resilience Nutri-Gardens use less water, rely on organic inputs, and recycle kitchen waste. They are less affected by market shocks and supply chain disruptions.

Role of Women and Community Empowerment

Women are the primary managers of kitchen gardens in most Indian households. Managing a Nutri-Garden gives them decision-making power over food and small income. Training programs by KVKs and universities have shown that when women are involved, the adoption rate and nutritional outcomes are much higher.

Community-level Nutri-Gardens in schools, Anganwadis, and SHG centers also serve as learning platforms. Children learn about nutrition, agriculture, and sustainability from an early age. This builds long-term behavior change.

Government Initiatives and Field Experiences

Telangana – Kutumba Nutri Garden Program: The Government of Telangana launched the Kutumba Nutri Garden initiative to establish kitchen gardens in every household across 29 districts. PJTSAU and KVKs provided training, seed kits, and technical support. Over 2 lakh households have adopted the model, reporting improved dietary diversity and reduced expenses.

Other States:

- **Odisha:** Nutri-Gardens in tribal areas linked with MGNREGA for labor support
- **Chhattisgarh:** School kitchen gardens improved mid-day meal quality
- **Kerala:** Urban kitchen gardens promoted under Haritha Keralam Mission

Institutional Support: ICAR promotes Nutri-Smart Villages where every household maintains a kitchen garden. FAO supports home garden programs as part of nutrition-sensitive agriculture. NGOs use Nutri-Gardens as an entry point for health and nutrition education.

Technical Package for Successful Nutri-Garden

- **Land Preparation:** Clear weeds, add 5kg compost per sq.m
- **Seed Selection:** Use high-yielding, disease-resistant varieties. Treat seeds with Trichoderma
- **Water Management:** Drip irrigation or mulching to save water
- **Nutrient Management:** Use vermicompost, jeevamrutham, and kitchen waste
- **Pest Management:** Neem-based sprays, yellow sticky traps, and companion planting
- **Continuous Planting:** Sow new seeds every 15 days for continuous harvest

Challenges and Solutions

Challenge	Solution
Lack of space in urban areas	Promote vertical, terrace, and container gardening
Water scarcity	Rainwater harvesting and mulching
Lack of awareness	Training through KVKs, YouTube, and SHGs
Pest and disease attack	IPM and use of bio-inputs
Seasonal gaps	Maintain seed bank and grow across seasons

Way Forward and Policy Recommendations

To make Nutri-Gardens a mass movement, the following steps are needed:

- **Include in Government Schemes:** Link Nutri-Gardens with Poshan Abhiyan, ICDS, and Mid-Day Meal
 - **Seed and Input Support:** Provide free or subsidized vegetable seed kits through agriculture departments
 - **Capacity Building:** Integrate kitchen gardening in school curriculum and SHG training
 - **Digital Extension:** Use mobile apps and videos for demonstration
 - **Research and Monitoring:** Universities should document impact on nutrition and income
- If every rural household adopts a Nutri-Garden, India can significantly reduce its vegetable import bill and improve public health outcomes.

Conclusion

Nutri-Gardens are more than a gardening activity. They are a tool for health, wealth, and empowerment. By turning small spaces into sources of nutrition, families can take control of their food and future. The model is low-cost, sustainable, and women-friendly. As we work toward a hunger-free India by 2030, Nutri-Gardens must be recognized as a core strategy. “Growing nutrition at the doorstep” is not just a slogan — it is a practical way to ensure that no family goes to bed without access to fresh, healthy food. What we teach today in our backyards will shape the health of tomorrow’s generation.

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ORNAMENTAL FISH FARMING: A PROFITABLE AGRIBUSINES**Harshrajsinh Mahendrasinh Zankat¹, Sanjaykumar Rambhai Vala²,
Devendra Solanki³ and Prakash V Parmar⁴**¹Senior Research Fellow, Matsya Vigyan Kendra, Kamdhenu University,
Mahuva-364290, Gujarat, India.²Senior Research Assistant, Fisheries Research and Training Centre,
Kamdhenu University, Mahuva-364290, Gujarat, India.³Fisheries Research and Training Centre, Kamdhenu University,
Mahuva-364290, Gujarat, India.⁴Professor and Head, Fisheries Research and Training Centre,
Kamdhenu University, Mahuva-364290, Gujarat, India.*Corresponding Email: vijaychaudhary30358@gmail.com**Introduction**

Ornamental fish farming is one of the fastest-growing sectors of aquaculture and has emerged as a profitable agribusiness worldwide. The culture of ornamental fishes is gaining increasing popularity due to the rising demand for aquarium fishes in domestic and international markets. More than 6,000 ornamental fish species are traded globally, with freshwater species accounting for nearly 90% of the market. Besides providing aesthetic value, ornamental fishes support employment generation, income diversification, and rural entrepreneurship, particularly for small-scale farmers, women, and youth. The enterprise requires relatively low investment, occupies limited space, and offers quick economic returns compared to many other farming activities. India possesses rich freshwater and marine fish biodiversity, creating immense potential for the development of the ornamental fish industry. Advances in breeding, nutrition, water quality management, and transportation have further improved production efficiency and fish survival. With increasing consumer interest, expanding export opportunities, and strong government support through fisheries development programmes, ornamental fish farming has become a sustainable and promising agribusiness with significant potential for future growth.

Status and Economic Importance of Ornamental Fish Farming

The ornamental fish industry has become one of the fastest-growing sectors of global aquaculture due to the increasing demand for aquarium fishes and aquatic plants. More than 125 countries are involved in the production and trade of ornamental fishes, with Asia accounting for a major share of global exports. The global ornamental fish market continues to expand, driven by rising consumer interest, urbanization, and the growing popularity of home and office aquariums. India possesses rich freshwater and marine fish biodiversity, with over 850 indigenous ornamental fish species offering significant potential for domestic production and export. Ornamental fish farming has emerged as a profitable agribusiness because it requires relatively low investment, limited land, and simple infrastructure while providing high economic returns. The sector generates employment opportunities for rural households, women, and young entrepreneurs through breeding, seed production, feed manufacturing, aquarium maintenance, and fish marketing. In addition, the ornamental fish industry contributes to foreign exchange earnings, promotes biodiversity conservation through captive breeding, and supports sustainable livelihood development. With increasing market demand, technological advancements, and government

support, ornamental fish farming has strong potential to become an important component of the blue economy and sustainable aquaculture development.

Major Ornamental Fish Species

Ornamental fishes are broadly classified into freshwater and marine species based on their habitat. Freshwater ornamental fishes dominate the global aquarium trade because they are easier to breed, hardy, and require lower maintenance than marine species. Popular freshwater ornamental fishes include Goldfish (*Carassius auratus*), Koi Carp (*Cyprinus rubrofuscus*), Guppy (*Poecilia reticulata*), Molly (*Poecilia sphenops*), Platy (*Xiphophorus maculatus*), Swordtail (*Xiphophorus hellerii*), Angelfish (*Pterophyllum scalare*), Discus (*Symphysodon* spp.), Zebrafish (*Danio rerio*), Oscar (*Astronotus ocellatus*), and Neon Tetra (*Paracheirodon innesi*). Marine ornamental fishes such as Clownfish (*Amphiprion ocellaris*), Blue Tang (*Paracanthurus hepatus*), Yellow Tang (*Zebrasoma flavescens*), Lionfish (*Pterois volitans*), and Butterflyfish (*Chaetodon* spp.) are highly valued for their vibrant colours and unique appearance. The selection of ornamental fish species depends on market demand, adaptability, breeding potential, and ease of culture, making species diversification an important factor for profitable ornamental fish farming.



Figure 1. Common ornamental fish species cultured in India.

Table 1. Common freshwater ornamental fish species.

Common Name	Scientific Name
Goldfish	<i>Carassius auratus</i>
Koi Carp	<i>Cyprinus rubrofuscus</i>
Guppy	<i>Poecilia reticulata</i>
Molly	<i>Poecilia sphenops</i>
Platy	<i>Xiphophorus maculatus</i>
Swordtail	<i>Xiphophorus hellerii</i>
Angelfish	<i>Pterophyllum scalare</i>
Discus	<i>Symphysodon</i> spp.
Zebrafish	<i>Danio rerio</i>

Infrastructure and Culture Systems

Proper infrastructure and suitable culture systems are essential for successful and profitable ornamental fish farming. The basic infrastructure includes breeding tanks, rearing tanks, glass aquariums, cement or FRP tanks, filtration units, aeration systems, water pumps, heaters, lighting, and water quality monitoring equipment. The choice of culture system depends on the fish species, production scale, and available investment. Small-scale farmers generally use glass aquariums and FRP tanks, whereas commercial farms employ cement tanks, earthen ponds, and indoor recirculating aquaculture systems (RAS) for large-scale production. Efficient filtration, continuous aeration, and regular water exchange help maintain optimum water quality, reduce disease outbreaks, and improve fish growth and survival. A well-designed culture system with proper biosecurity and environmental control enhances production efficiency, minimizes operational costs, and ensures the sustainable development of ornamental fish farming.

Water Quality Management

Maintaining optimum water quality is one of the most important factors for successful ornamental fish farming, as it directly influences fish health, growth, reproduction, and survival. Key water quality parameters include temperature (24–28°C), pH (6.5–7.5), dissolved oxygen (above 5 mg/L), ammonia and nitrite (near zero), nitrate (below 50 mg/L), and suitable water hardness. Regular monitoring, efficient filtration, continuous aeration, and periodic water exchange help maintain a healthy aquatic environment and prevent the accumulation of toxic substances. Good water quality reduces stress, minimizes disease outbreaks, enhances feed utilization, and improves the colour and overall appearance of ornamental fishes. Therefore, effective water quality management is essential for achieving high productivity and sustainable ornamental fish farming.

Nutrition and Feeding Management

Proper nutrition and feeding management are essential for maintaining the health, growth, coloration, reproductive performance, and overall quality of ornamental fishes. A nutritionally balanced artificial diet containing adequate amounts of protein, lipids, carbohydrates, vitamins, minerals, and essential fatty acids is required to support optimum growth and physiological functions. Protein is the most important nutrient in ornamental fish diets, with 30–45% crude protein generally recommended for most ornamental fish species, while larvae and juveniles require 40–50% protein to support rapid growth and development. Lipids (5–10%) serve as a major energy source and provide essential fatty acids, whereas carbohydrates (20–30%) supply additional energy and improve feed utilization. Vitamins and minerals play vital roles in metabolism, immunity, skeletal development, and colour enhancement. Commercial ornamental fish feeds are available as flakes, pellets, granules, micro-pellets, and floating or sinking feeds, while live feeds such as *Artemia*, *Daphnia*, *Moina*, *Tubifex*, and bloodworms are widely used for larvae, broodstock, and high-value species. Feeding should be carried out two to three times daily in small quantities to minimize feed wastage and maintain water quality. Proper feeding practices improve feed conversion ratio (FCR), growth performance, survival, reproductive efficiency, disease resistance, and body coloration, thereby enhancing the profitability and sustainability of ornamental fish farming.

Breeding and Seed Production

Breeding and seed production are the foundation of successful ornamental fish farming, ensuring a continuous supply of healthy and high-quality fish for commercial production. Most ornamental fish species breed naturally under favourable environmental conditions, while some species

require induced breeding using hormonal techniques. Successful breeding depends on the selection of healthy broodstock, proper male-to-female ratio, optimum water quality, suitable temperature (24–28°C), adequate dissolved oxygen, and appropriate spawning substrates or breeding tanks. After spawning, fertilized eggs are carefully incubated under controlled conditions to achieve high hatching success. The larvae are initially fed with live feeds such as infusoria, rotifers, *Artemia* nauplii, *Moina*, and *Daphnia*, followed by a gradual transition to formulated artificial feeds. Proper hatchery management, broodstock nutrition, disease prevention, and regular water quality monitoring improve spawning performance, larval survival, seed quality, and overall production efficiency. The adoption of improved breeding technologies and scientific hatchery practices has significantly increased the commercial production of ornamental fish seed, making ornamental fish farming a profitable and sustainable aquaculture enterprise.

Health Management and Disease Control

Effective health management and disease control are essential for maintaining the survival, growth, and market value of ornamental fishes. Good management practices, including the use of healthy seed, proper nutrition, regular water quality monitoring, and optimum stocking density, help reduce stress and prevent disease outbreaks. Common diseases in ornamental fishes are caused by bacteria (*Aeromonas*, *Pseudomonas*, *Flavobacterium*), fungi (*Saprolegnia* spp.), parasites (*Ichthyophthirius multifiliis*, *Trichodina* spp., *Dactylogyrus* spp.), and viruses. Clinical signs include loss of appetite, abnormal swimming, skin ulcers, fin rot, excessive mucus secretion, white spots, and gill damage. Maintaining good water quality, regular tank cleaning, quarantine of newly introduced fishes, disinfection of equipment, and timely diagnosis are essential preventive measures. When required, approved therapeutics, probiotics, and salt or chemical treatments should be applied under recommended guidelines. A strong biosecurity programme combined with proper health monitoring and disease prevention strategies improves fish welfare, reduces mortality, enhances production efficiency, and ensures sustainable and profitable ornamental fish farming.

Packaging, Transportation, and Marketing

Proper packaging, transportation, and marketing are essential for maintaining the quality, survival, and commercial value of ornamental fishes. Healthy fishes are packed in strong polyethylene bags containing one-third clean water and two-thirds oxygen to ensure adequate oxygen supply during transport. The bags are securely sealed and placed in insulated thermocol or cardboard boxes to maintain a stable temperature and minimize stress. Water conditioners, anti-stress agents, and sedatives may be used, where appropriate, to improve fish survival during long-distance transportation. Careful handling and proper packing techniques reduce physical injuries and mortality. Ornamental fishes are marketed through aquarium shops, wholesalers, retailers, hatcheries, exhibitions, online platforms, and export markets. Increasing domestic demand, expanding international trade, and the growth of e-commerce have created significant business opportunities for ornamental fish farmers. Efficient packaging, safe transportation, and well-planned marketing strategies enhance product quality, customer satisfaction, profitability, and the overall growth of the ornamental fish industry.

Government Schemes and Entrepreneurship Opportunities

The Government of India has launched several initiatives to promote ornamental fish farming as a sustainable and profitable agribusiness. The Pradhan Mantri Matsya Sampada Yojana (PMMSY) provides financial assistance for the establishment of ornamental fish hatcheries, breeding units,

rearing facilities, aquarium units, and marketing infrastructure. Additional support is available through the Fisheries and Aquaculture Infrastructure Development Fund (FIDF), National Fisheries Development Board (NFDB), and various state fisheries departments, which offer subsidies, skill development programmes, technical training, and credit support for entrepreneurs. Ornamental fish farming requires relatively low investment, limited land, and simple infrastructure, making it an attractive enterprise for rural youth, women, self-help groups (SHGs), and start-up entrepreneurs. The increasing domestic demand, expanding export market, and growth of online aquarium businesses have further enhanced income and employment opportunities. With improved access to modern technologies, government support, and organized marketing systems, ornamental fish farming has significant potential to strengthen rural livelihoods, promote self-employment, and contribute to the sustainable growth of the aquaculture sector.

Challenges and Future Prospects

Despite its high profitability and growing market demand, ornamental fish farming faces several challenges that limit its sustainable development. Major constraints include the limited availability of quality broodstock and seed, disease outbreaks, poor water quality management, inadequate technical knowledge, and high transportation losses. The industry also faces challenges related to limited access to quality feed, insufficient infrastructure, unorganized marketing systems, and dependence on imported ornamental fish species. In addition, climate change, increasing production costs, and stringent international quarantine and biosecurity regulations can affect production and export performance. However, the future prospects of ornamental fish farming remain highly promising due to increasing domestic and global demand, technological advancements in breeding and hatchery management, improved nutrition and disease control, and the expansion of online marketing platforms. Government initiatives, entrepreneurship development programmes, and the adoption of sustainable aquaculture practices are expected to further strengthen production, employment, and export opportunities, making ornamental fish farming a profitable and sustainable agribusiness for the future.

Conclusion

Ornamental fish farming has emerged as a profitable and rapidly growing agribusiness, offering significant opportunities for income generation, employment, and export earnings. The adoption of scientific breeding techniques, balanced nutrition, effective water quality management, disease prevention, and improved packaging and transportation has greatly enhanced production efficiency and fish quality. In addition, government support, technological advancements, and expanding domestic and international markets are accelerating the growth of the ornamental fish industry. However, addressing challenges related to quality seed production, disease management, infrastructure, and marketing remains essential for sustainable development. With proper technical knowledge, entrepreneurship, and modern aquaculture practices, ornamental fish farming has immense potential to become a sustainable, profitable, and high-value enterprise that contributes to rural livelihoods, economic growth, development of the aquaculture sector.

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OZONE TREATMENT FOR SEAFOOD SAFETY

**S. T. Dhivya Bharathi¹, L. Vinoth Kumar^{2*}, G. Dhivagar¹,
M. Dhanu Pradeep¹, R. Gayathri¹ and E. K. Devipriya¹**

^{1 3 4 5 6}B.F.Sc Scholar, Department of Fish Processing Technology,
TNJFU- Dr.MGR. Fisheries College and Research Institute, Ponneri,
Thiruvallur District, Tamil Nadu 601204

²Assistant professor, Department of Fish Processing Technology,
TNJFU - Fisheries College and Research Institute, Thoothukudi-628 008, Tamil Nadu.

*Corresponding Email: vinothkumar@tnfu.ac.in

Abstract

Ozone (O₃), a powerful oxidising agent with broad-spectrum antimicrobial activity, has emerged as a compelling non-thermal intervention for improving seafood safety and quality. Aqueous ozone concentrations of 0.5–2.0 mg/L achieve 2–5 log reductions in bacterial counts on fish fillets, shrimp, and bivalves, while gaseous ozone at 1–10 ppm extends refrigerated shelf life by 30–60%. This article reviews ozone's chemistry, applications, efficacy data, sensory/nutritional effects, limitations, and emerging combinatorial strategies.

Keywords: Ozone, seafood safety, antimicrobial treatment, non-thermal processing, Vibrio, Norovirus, shelf-life extension, HACCP, GRAS, hurdle technology.

Introduction

Seafood is a vital global protein source for over 3.3 billion people, yet it accounts for ~15% of foodborne disease outbreaks due to pathogens including *Vibrio parahaemolyticus*, *Listeria monocytogenes*, *Salmonella* spp., and Norovirus. Conventional preservation methods (chlorine washing, icing, cold storage) carry drawbacks including chemical residues and environmental concerns. Ozone (O₃), recognised as GRAS by the FDA since 2001, offers a powerful eco-friendly alternative — it decomposes into oxygen, leaves no harmful residues, and delivers superior antimicrobial performance.

Chemistry and Antimicrobial Mechanism

Ozone is generated on-site via corona discharge or UV irradiation. With a standard reduction potential of +2.07 V — exceeding chlorine (+1.36 V) and chlorine dioxide (+1.50 V) — it is the most potent chemically feasible oxidant approved for food contact. Its half-life in water ranges from 20–30 minutes (distilled water, 20°C) to under 5 minutes (seawater), ensuring no persistent residue but demanding careful operational control.

Ozone inactivates microorganisms through four concurrent mechanisms:

- Cell membrane disruption via lipid peroxidation of phospholipid bilayers
- Protein oxidation by hydroxyl radicals (•OH), superoxide anions, and singlet oxygen
- DNA/RNA strand breaks and cross-linking that prevent microbial replication
- Viral capsid degradation preventing host cell attachment (e.g., Norovirus)

The multi-target nature of ozone's action makes development of microbial resistance extremely unlikely — a key advantage over antibiotic or single-mechanism disinfectants.

Applications in Seafood Processing**Aqueous Ozone Washing (Fish Fillets and Crustaceans)**

Immersion of Atlantic salmon, tilapia, and cod in 0.5–2.0 mg/L ozonated water for 5–10 minutes reduces total viable counts (TVC) by 2–4 log₁₀ CFU/g and extends refrigerated shelf life from 8–10 days to 12–16 days. For shrimp, treatment at 1.0–1.5 mg/L reduces *Vibrio parahaemolyticus* by 3–4 log₁₀ CFU/g and delays melanosis (black spot) onset by 2–3 days without altering texture or colour. Continuous low-dose ozonation (0.01–0.05 mg/L) in live-haul tanks controls pathogen loads without stressing the animals.

Bivalve Mollusc Depuration

Oysters, mussels, and clams bioaccumulate Norovirus and bacterial pathogens from faecally contaminated waters. Ozone-assisted depuration at 0.3–0.5 mg/L significantly outperforms UV-alone treatment, achieving up to 2.5 log₁₀ Norovirus reduction and complete elimination of *Vibrio vulnificus* and *Salmonella* within 24–48 hours.

Gaseous Ozone in Cold Storage

Continuous low-level gaseous ozone (1–2 ppm) in refrigerated chambers (2–4°C) delivers 30–50% longer shelf life versus conventional cold storage, suppressing *Pseudomonas* spp. and moulds. Doses above 5 ppm risk lipid oxidation and discolouration in fatty fish (mackerel, herring), so careful dose optimisation is essential.

Table 1. Selected Microbial Inactivation Efficacy Data

Target Pathogen	Seafood Matrix	Ozone Treatment	Log Reduction	Key Reference
<i>Vibrio parahaemolyticus</i>	Shrimp	1.0 mg/L aq., 5 min	3.4–4.0 log	Gonçalves & Defendi (2016)
<i>Listeria monocytogenes</i>	Salmon fillet	2.0 mg/L aq., 10 min	2.8–3.5 log	Cai et al. (2015)
<i>Salmonella Typhimurium</i>	Oyster	0.5 mg/L aq., 30 min	3.0–3.8 log	Lees (2000)
Norovirus GI & GII	Oyster (depuration)	0.3 mg/L aq., 48 h	2.3–2.7 log	Cromeans et al. (2010)
Total Viable Count	Cod fillet	1.5 mg/L aq., 5 min	2.5–3.2 log	Kim et al. (2003)
<i>Pseudomonas fluorescens</i>	Tuna, cold storage	2 ppm gas, continuous	1.5–2.0 log/week	Dermiki et al. (2008)

Sensory Quality and Nutritional Integrity

When ozone concentration, contact time, and temperature are correctly controlled, sensory quality is maintained or marginally improved relative to chlorine-treated controls. Studies on cod, salmon, and shrimp show no significant differences in colour (L*, a*, b*), cooked texture, or overall acceptability. Excess ozone (>2.0 mg/L aqueous; >10 ppm gaseous) can bleach salmonid/shrimp pigmentation and produce off-flavours in fatty fish — but these thresholds are well above recommended operational levels.

Omega-3 fatty acids (EPA and DHA), protein quality (PDCAAS), and fat-soluble vitamins (A, D, E, K) are all preserved at GMP-consistent ozone exposures. Lipid oxidation assays (TBARS, peroxide value) confirm that primary oxidation products remain within acceptable limits.

Limitations and Challenges:

Key practical obstacles to widespread adoption include:

- On-site generation required (cannot be stored): capital costs of USD 20,000–200,000 depending on scale
- Rapid ozone consumption by organic load (blood, slime, mucus) — real-time monitoring and feed-forward control systems are essential
- Material compatibility: equipment must be fabricated from SS 316L, titanium, PTFE, or fluoropolymers; common elastomers (rubber, neoprene, EPDM) deteriorate rapidly
- Standardised dose-response models for regulatory harmonisation remain incomplete
- Long-term effects on highly unsaturated species (mackerel, sardine) at low continuous gaseous doses need further study

Emerging Combinatorial (Hurdle) Technologies

Combining ozone with complementary mild treatments achieves synergistic microbial inactivation while minimising quality impact:

- Ozone + UV irradiation: synergistic Norovirus and Cryptosporidium inactivation in bivalve depuration systems
- Ozone + Modified Atmosphere Packaging (MAP): shelf life extended to 21–28 days at 2°C vs. 12–14 days for MAP alone
- Ozone + Electrolysed Water (EW): complementary oxidative mechanisms delivering >5 log TVC reductions on shrimp
- Ozone + Natural Antimicrobials (thymol, carvacrol): synergistic activity against *Listeria* and *Salmonella* on salmon fillets

Summary of Microbial Inactivation Efficacy

Target Pathogen / Organism	Seafood Matrix	Ozone Conc. & Mode	Log Reduction	Key Reference
<i>Vibrio parahaemolyticus</i>	Shrimp	1.0 mg/L aq., 5 min	3.4–4.0 log	Gonçalves & Defendi (2016)
<i>Listeria monocytogenes</i>	Salmon fillet	2.0 mg/L aq., 10 min	2.8–3.5 log	Cai et al. (2015)
<i>Salmonella Typhimurium</i>	Oyster	0.5 mg/L aq., 30 min	3.0–3.8 log	Lees (2000)
Norovirus GI & GII	Oyster (depuration)	0.3 mg/L aq., 48 h	2.3–2.7 log	Cromeans et al. (2010)
Total Viable Count (TVC)	Cod fillet	1.5 mg/L aq., 5 min	2.5–3.2 log	Kim et al. (2003)
<i>Pseudomonas fluorescens</i>	Tuna, cold storage	2 ppm gas, continuous	1.5–2.0 log/week	Dermiki et al. (2008)
<i>Aspergillus</i> spp. (mould)	Dried squid	5 ppm gas, 30 min	3.0–4.5 log	Tiwari et al. (2010)
<i>Aeromonas hydrophila</i>	Trout fillet	1.0 mg/L aq., 8 min	3.0–3.5 log	Goncharuk et al. (2010)

Conclusion

Ozone technology offers a scientifically rigorous, environmentally responsible, and commercially viable solution to seafood safety and spoilage. Key conclusions:

- Aqueous ozone at 0.5–2.0 mg/L achieves consistent 2–5 log pathogen reductions without compromising nutritional or sensory quality
- Gaseous ozone at 1–2 ppm in cold storage extends shelf life by 30–60%
- Ozone-assisted bivalve depuration markedly improves Norovirus reduction vs. UV alone
- Combinatorial hurdle strategies incorporating ozone represent the most promising pathway for next-generation seafood safety systems

Future research priorities

standardised dose-response protocols, validation against emerging pathogens, techno-economic analysis of large-scale implementation, and consumer communication strategies.

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PADDY STUBBLE INCORPORATION: A SUSTAINABLE APPROACH FOR SOIL HEALTH AND CLEAN ENVIRONMENT

P. Sadvi¹, N. Mahesh², A. Nagaraju³ and U. Sravanthi⁴

¹Subject Matter Specialist (Agricultural Extension),
Krishi Vigyan Kendra, Bellampalli, Mancherla

²Subject Matter Specialist (Crop Production),
Krishi Vigyan Kendra, Bellampalli, Mancherla

³Subject Matter Specialist (Plant protection),
Krishi Vigyan Kendra, Bellampalli, Mancherla

⁴Scientist (Horticulture), ARI, Rajendranagar, PJTAU

*Corresponding Email: purma.sadvi@gmail.com

Rice is one of the most important staple crops in India and forms the backbone of food security for millions of people. With the widespread use of combine harvesters, a large quantity of paddy straw and stubble remains in the field after harvesting. Managing this residue has become a major challenge for farmers. To clear fields quickly for the next crop, many farmers burn the crop residue. Although this method is quick and inexpensive, it causes severe environmental pollution and results in the loss of valuable plant nutrients. Incorporating paddy stubble into the soil is an eco-friendly and sustainable alternative that benefits both farmers and the environment.

Magnitude of the Paddy Residue Problem

India generates a huge amount of crop residues every year. It is estimated that about 500 million tonnes of crop residues are produced annually in the country, with rice straw contributing nearly 34 percent of the total residue. Out of this, about 140 million tonnes remain surplus, and nearly 92 million tonnes are burned in the fields due to lack of proper management practices.

In fields harvested by combine harvesters, about 12–13 tonnes of residue per hectare are left behind. This includes nearly 7 tonnes of standing stubble and about 5–6 tonnes of loose straw. Burning such large quantities of residue releases harmful gases such as carbon dioxide, methane and nitrous oxide, which contribute to air pollution and climate change. In addition, residue burning destroys beneficial soil microorganisms and reduces soil fertility.

Nutrient Loss Due to Stubble Burning

Crop residues contain significant quantities of plant nutrients that are lost during burning. Research studies indicate that burning one tonne of crop residue results in the loss of approximately:

- 5.5 kg Nitrogen
- 2.3 kg Phosphorus
- 25 kg Potassium
- 1.2 kg Sulphur

Besides these nutrients, burning also causes the complete loss of organic carbon, which is vital for maintaining soil health. Continuous burning therefore increases dependence on chemical fertilizers and raises the cost of cultivation.

Benefits of Paddy Stubble Incorporation

Incorporating paddy straw and stubble directly into the soil converts the residue into a valuable resource. This practice offers several agronomic, economic, and environmental benefits.

1. Improvement in Soil Fertility

Paddy straw contains essential nutrients that can be recycled through incorporation. Studies have shown that incorporation of rice straw can add approximately 14 kg nitrogen, 7 kg phosphorus, 63 kg potassium and 3 kg sulphur per acre to the soil. It also contributes a large amount of organic matter, which improves soil fertility over time.

Long-term studies have indicated that soil organic carbon increased from 0.33 percent to about 0.75 percent where crop residues were incorporated or retained in the field.

Nutrient Value of Rice Straw

Rice straw contains significant quantities of plant nutrients which can be recycled back to the soil through residue incorporation.

Nutrient	Approximate Nutrient Content in 1 tonne of Rice Straw
Nitrogen (N)	5 – 7 kg
Phosphorus (P ₂ O ₅)	1 – 2 kg
Potassium (K ₂ O)	12 – 25 kg
Sulphur (S)	1 – 2 kg
Organic Carbon	300 – 400 kg

Incorporating rice straw into the soil helps recycle these nutrients, improve soil organic matter, and reduce dependence on chemical fertilizers.

Table 1: Nutrient Loss Due to Burning of Rice Straw

Burning crop residues results in the loss of valuable plant nutrients that could otherwise improve soil fertility.

Nutrient	Quantity Lost When 1 Tonne of Rice Straw is Burned
Nitrogen (N)	5.5 kg
Phosphorus (P ₂ O ₅)	2.3 kg
Potassium (K ₂ O)	25 kg
Sulphur (S)	1.2 kg
Organic Carbon	Almost completely lost

Continuous burning of residues leads to nutrient depletion and increases dependence on chemical fertilizers.

Table 2: Comparison between Stubble Burning and Stubble Incorporation

Aspect	Stubble Burning	Stubble Incorporation
Soil Fertility	Nutrient loss	Nutrient recycling
Soil Organic Matter	Decreases	Increases
Soil Microorganisms	Destroyed by heat	Encouraged
Air Quality	Causes severe pollution	No pollution
Fertilizer Requirement	Higher	Reduced
Long-term Soil Health	Degrades soil	Improves soil health
Crop Productivity	May decline over time	Improves productivity

2. Increase in Crop Productivity

Residue incorporation improves soil biological activity and nutrient availability. Research findings show that incorporation of crop residues increased soil nitrogen content by about 27 percent and grain nitrogen uptake by nearly 35 percent, resulting in about 23 percent higher system productivity compared to residue removal.

3. Improvement in Soil Physical Properties

Incorporation of crop residues improves soil structure and enhances soil physical properties. It:

- Improves soil aggregation
- Reduces soil bulk density
- Enhances water infiltration and water-holding capacity

These improvements help crops tolerate dry spells and improve the efficiency of fertilizer use.

4. Reduction in Fertilizer Requirement

As residues decompose and release nutrients gradually, they reduce the requirement for chemical fertilizers. Farmers can save a portion of fertilizer costs by recycling nutrients through residue incorporation.

5. Enhancement of Soil Biological Activity

Residue incorporation stimulates the activity of beneficial microorganisms such as bacteria and fungi. These organisms play an important role in nutrient cycling, decomposition of organic matter, and maintaining soil health.

6. Environmental Protection

Avoiding residue burning helps reduce air pollution and greenhouse gas emissions. It also prevents the formation of smog and protects human and animal health. Incorporation supports soil biodiversity and contributes to climate-smart agriculture.

7. Long-Term Sustainability of Cropping Systems

Continuous incorporation of crop residues improves soil health, which is essential for sustaining productivity in rice-based cropping systems. Healthy soils also improve resilience to climate variability.

Methods of Paddy Stubble Incorporation

Farmers can adopt different technologies to manage crop residues effectively without burning:

- Rotavator or disc harrow for direct incorporation of residues
- Straw chopper followed by ploughing to mix straw into the soil
- Happy Seeder or Super Seeder for sowing wheat directly into standing residue
- Application of microbial decomposers to accelerate straw decomposition

These technologies help convert crop residues into valuable organic matter within the soil.

Conclusion

Paddy stubble incorporation is a sustainable and environmentally friendly practice that transforms crop residues into a valuable resource. By recycling nutrients, improving soil health, and enhancing crop productivity, it provides long-term benefits to farmers and the ecosystem. Promoting residue incorporation through awareness programs, training, and support for farm machinery will help farmers adopt this eco-friendly practice and ensure the sustainability of rice-based farming systems.

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THE PALMYRA PALM: NATURE'S SUPERHERO FOR A SUSTAINABLE FUTURE

Siva Sakthi T^{1*}, Sabarinathan G² and Gomathy M³

¹Project Assistant, Dept. of Agri. Microbiology,
Agricultural College and Research Institute, TNAU, Madurai

²Associate Professor, Dept. of Agri. Microbiology,
Agricultural College and Research Institute, TNAU, Madurai

³Associate Professor, Dept. of Agri. Microbiology,
VOC Agricultural College and Research Institute, Killikum

*Corresponding Email: sivasakthit1997@gmail.com

Abstract

The palmyrah palm (*Borassus flabellifer* L.) is a multipurpose species of considerable nutritional, economic, ecological, and cultural importance. Nearly every part of the palm is utilized for the production of food, beverages, fibres, timber, and medicinal products, resulting in minimal waste. Edible products such as neera, fruits, tubers, and seedlings are rich in essential nutrients and offer significant opportunities for value addition. The palm also supports rural livelihoods and contributes to environmental sustainability through soil conservation, carbon sequestration, and biodiversity enhancement. Moreover, its abundance of bioactive compounds imparts diverse pharmacological properties, highlighting its potential as a source of functional foods and natural therapeutics. The versatility and resilience of the palmyrah palm underscore its importance in sustainable resource management and climate-resilient development.

Keywords: *Borassus flabellifer*; palmyrah palm; neera; value addition; functional foods; sustainability; climate resilience.

Introduction

The palmyra palm, often referred to as the “tree of life,” is a multipurpose species whose various parts are utilized for food, beverages, fibre, fodder and timber ensuring that virtually no part of the tree goes to waste. India supports the world’s largest population of palmyra palms, with approximately 122 million trees. Although edible products derived from the palm are nutritionally valuable, their commercial potential remains largely unrealized because of limited value addition and product diversification (Rao *et al.*, 2021).

Beyond meeting daily needs, the palmyra palm supports livelihoods, preserves cultural traditions, and contributes to environmental conservation through its drought tolerance and ability to stabilize fragile ecosystems. In an era marked by climate change and the urgent need for sustainable resources, this humble palm offers a powerful example of how nature can inspire resilient and circular ways of living. Exploring its many benefits reveals why the palmyra palm truly deserves its title as nature’s superhero for a sustainable future (Kuldeep *et al.*, 2026).

In South India, the sweet sap tapped from the inflorescence is particularly cherished and serves as an important raw material for the production of palm sugar. Edible products derived from the palmyra palm are excellent sources of vitamins and minerals; however, their commercial development has remained limited owing to inadequate value addition. Among the palm’s many

edible products, the sweet sap extracted from the inflorescence is particularly significant, serving as the primary raw material for palm sugar production. In addition, the soft endosperm of the immature fruit, known as “nungu,” is a popular summer delicacy, much like tender coconut (Sarkar *et al.*, 2023).

Sustainable living is often associated with clean energy, recycling, and environmentally conscious habits. However, long before these concepts gained prominence, the palmyra palm had already been supporting a sustainable way of life. This remarkable tree provides an array of valuable resources, from nutritious foods and herbal remedies to durable materials for construction, all while fostering ecological balance. Its exceptional adaptability and multifaceted uses make the palmyra palm a powerful example of how nature can guide us toward a greener and more resilient future (Andrade and Raja, 2023).

The Palmyra Palm: A Remarkable Tree of Many Uses

Native to South and Southeast Asia, the palmyra palm (*Borassus flabellifer*) has supported human societies for centuries. Renowned for its exceptional versatility, this remarkable tree provides a wealth of resources while generating almost no waste. Nearly every part of the palm is put to productive use, making it a shining example of sustainable living (Franco *et al.*, 2020).

Leaves: The leaves of the palmyra palm are remarkably versatile, serving as materials for roof thatching, fencing, and the crafting of everyday items such as mats, baskets, fans, hats, umbrellas, buckets, and sandals. Dried, senescent leaves are commonly used as cooking fuel and once they have fulfilled their roles in thatching or fencing, they are often recycled by farmers as organic fertilizer, ensuring that virtually no part of the leaf goes to waste (Kuldeep *et al.*, 2026).

Matured fruit: The fleshy mesocarp of the mature palmyra fruit yields a small quantity of natural fibre. Though limited in amount, this fibre is valued for its texture and is traditionally processed into a variety of handicrafts, including decorative items and toys. Its utilization not only adds value to the fruit but also supports local artisans and promotes the sustainable use of palmyra resources (Shetty *et al.*, 2026).

Petiole and leaf blade: The petiole and leaf blade of the palmyrah palm yield strong and durable fibres with diverse applications. Petiole fibres are long and tough, making them ideal for ropes used in house construction and boat building. Fibres from the leaf blades are hard, stiff, and highly resistant to wear, making them suitable for the manufacture of brushes, brooms, handicrafts, and other decorative products. Their biodegradability and versatility further underscore their value as sustainable raw materials for rural industries (Krishnaveni *et al.*, 2020).

Trunk: The hollowed trunk of the palmyrah palm has traditionally been valued for the manufacture of water pipes owing to its strength, durability, and natural resistance to decay (Ramachandran, 2008).

Timber and fibres: Timber and fibres are among the most valuable commercial by-products of the palmyrah palm. A single palm yields several distinct types of fibres, including loose fibres from the base of the leaf stalk, long fibres from the petiole, fibres from the stem interior, coir-like fibres from the fruit pericarp, and fibrous material from the leaves. These fibres are traditionally crafted into baskets, cords, ropes, mats, and other utility items that reflect local artisanal skills. In particular, fibres from the leaf base serve as an excellent raw material for brush manufacture and constitute an important source of income and export revenue in many regions of India. The

durable timber of the palm further enhances its economic value and supports a variety of construction and household applications (Behera and Nayak, 2022).

Neera: Neera, the unfermented sap tapped from the inflorescence of the palmyrah palm, constitutes one of the most economically significant products of the species. It is a nutrient-rich beverage containing appreciable amounts of minerals, particularly calcium, phosphorus, and iron, together with vitamins such as vitamin A, thiamin, riboflavin, and niacin. Owing to its nutritional composition, neera is traditionally regarded as having mild laxative and diuretic properties. Nevertheless, its high fermentable sugar content renders it highly perishable, and rapid spontaneous fermentation can lead to the formation of alcohol within a few hours of tapping if appropriate preservation measures are not adopted (Srivastava *et al.*, 2017).

Endosperm: The translucent, jelly-like endosperm of young palmyrah fruits, typically harvested 60–70 days after fruit set, is highly nutritious and widely consumed as a refreshing seasonal delicacy during the summer months (Krishnaveni *et al.*, 2020).

Tuber (Apocolon): The mature apocolon (tuber) of the palmyrah palm is a brittle, carbohydrate-rich storage organ that detaches readily from the seedling. Harvesting at approximately 135 days after sowing is considered optimal to obtain maximum yield and desirable quality for culinary and processing purposes (Krishnaveni *et al.*, 2020).

Fruit: The ripe palmyrah fruit contains a soft, orange-yellow mesocarp that is sweet, dense, and highly palatable. This edible pulp is a valuable source of vitamins A and C and is consumed fresh or processed into various food products. In addition, the fibrous outer layer of the mature fruit is edible and may be eaten raw or after boiling or roasting, thereby contributing to the comprehensive utilization of the fruit (Behera and Nayak, 2022).

Spongy Haustorium: The spongy haustorium that develops within the seed during germination is a sweet, edible structure that is widely relished as a traditional delicacy owing to its soft texture and pleasant taste (Krishnaveni *et al.*, 2020).

Seedlings: Peeled palmyrah seedlings are consumed either fresh or after sun-drying and may be eaten raw or prepared using a variety of traditional cooking methods. The seedlings are also a source of starch, which is commonly used to prepare nutritious gruels and other dishes, often combined with rice, herbs, chilli peppers, fish, or similar ingredients to enhance their flavor and nutritional value (Ranjani and Vathsala, 2023).

Panachoru: Panachoru” is a traditional edible cake obtained from the apical portion of the palmyrah palm after the crown is removed. Formed from the tender tissues at the base of the emerging leaves, it is valued as a local delicacy and consumed fresh in many palmyrah-growing regions (Ranjani and Vathsala, 2023).

Environmental benefits of the palmyra palm:

The palmyrah palm provides significant environmental benefits that support sustainable land use and ecosystem resilience. Its extensive and deep-rooted system effectively stabilizes the soil, thereby reducing erosion and enhancing the structural integrity of landscapes susceptible to flooding, drought and desertification. Consequently, the species is well suited for reforestation and agroforestry initiatives, particularly in marginal and arid regions. In addition, the palm contributes to climate-change mitigation through the sequestration of atmospheric carbon dioxide in its long-lived biomass. Palmyrah plantations also serve as habitats for diverse flora and

fauna, promoting biodiversity and improving ecological stability. Owing to its exceptional tolerance to harsh environmental conditions and minimal input requirements, the palmyrah palm represents a valuable component of sustainable and climate-resilient production systems (Shetty *et al.*, 2026).

Nutritional and Therapeutic Attributes of the Palmyrah Palm:

The palmyrah palm is recognized as a valuable source of bioactive compounds, including polyphenols, flavonoids, saponins, steroidal glycosides, vitamins, minerals, and carbohydrates, which underpin its diverse medicinal and nutritional attributes. Scientific investigations have demonstrated that extracts from various plant parts possess antioxidant, anti-inflammatory, antimicrobial, analgesic, antipyretic, hypoglycemic, and cytoprotective activities. In traditional systems of medicine, the roots, bark, inflorescences, fruits, and sap have long been employed to alleviate digestive and respiratory disorders, skin ailments, and hepatic dysfunction. Furthermore, products such as neera, toddy, and palm jaggery provide essential micronutrients and are valued for their tonic, diuretic, and mild laxative effects. Collectively, these findings highlight the considerable potential of palmyrah as a source of functional foods and natural therapeutic agents, warranting further phytochemical and clinical investigations (Prasad *et al.*, 2023).

Palmyrah Palm: A Symbol of Sustainability:

The palmyrah palm represents an enduring example of sustainable living and prudent resource use. Amid growing concerns over climate change, deforestation, and the depletion of natural resources, this multipurpose species offers a renewable supply of food, medicinal products, fibres, and construction materials while simultaneously supporting environmental conservation. Its ability to thrive in arid and marginal lands, coupled with its contributions to soil stabilization, carbon sequestration, and biodiversity enhancement, underscores its significance in climate-resilient agriculture. Consequently, the palmyrah palm stands as a model for sustainable development and a valuable asset for communities seeking environmentally responsible livelihoods (Samadharmam *et al.*, 2025).

Conclusion

The palmyrah palm exemplifies sustainable and circular resource use, with nearly all parts of the tree contributing to nutrition, livelihoods, traditional medicine, and environmental conservation. Its rich nutrient profile, diverse bioactive constituents, and wide range of value-added products indicate substantial scope for further utilization and commercialization. Continued research, product diversification, and conservation efforts will be essential to fully realize the potential of this valuable and resilient species for a sustainable future.

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NEXT-GENERATION AGRICULTURE: BRIDGING REGENERATIVE PRINCIPLES WITH SMART FARMING

K. N. Tiwari

Ex. Director, International Plant Nutrition Institute, India Programme
4/861, Hanumat Kripa, Gomati Nagar Extension, Lucknow 226010
Corresponding Email: kashinathtiwari730@gmail.com

Abstract

Indian agriculture has achieved remarkable success in ensuring food security; however, the sector faces mounting challenges arising from climate change, soil degradation, declining resource-use efficiency, groundwater depletion, biodiversity loss, and increasing production costs. Simultaneously, rapid advancements in precision agriculture, artificial intelligence (AI), remote sensing, drones, Internet of Things (IoT), and digital decision-support systems provide unprecedented opportunities to improve agricultural sustainability. Regenerative agriculture emphasizes restoring soil health, enhancing biodiversity, improving ecosystem services, and increasing carbon sequestration, while smart farming technologies optimize resource management and productivity through data-driven decision-making. Integrating these approaches offers a transformative pathway toward sustainable, climate-resilient, and profitable agriculture. This paper explores the concept of next-generation agriculture through the convergence of regenerative principles and smart farming technologies in the Indian context. The paper highlights opportunities for enhancing soil health, climate resilience, resource-use efficiency, biodiversity conservation, and farmer profitability while identifying policy and research priorities necessary for large-scale adoption.

Keywords: Regenerative agriculture, Smart farming, Precision agriculture, Climate resilience, Sustainable food systems, Digital agriculture

Introduction

Indian agriculture has undergone a remarkable transformation since independence, evolving from a food-deficit system dependent on imports to one of the world's largest and most diversified agricultural economies. Food grain production has increased more than six-fold over the past seven decades, enabling the country to achieve self-sufficiency in food and emerge as a significant exporter of agricultural commodities. This progress has been driven by technological advancements, improved crop varieties, irrigation expansion, mechanization, and increased use of fertilizers and other agricultural inputs. However, the sustainability of these achievements is increasingly being challenged by the adverse consequences of intensive agricultural practices. Excessive dependence on chemical fertilizers and pesticides, continuous monocropping, groundwater overexploitation, residue burning, and indiscriminate tillage have contributed to declining soil health, nutrient imbalances, reduced biodiversity, and environmental degradation (Lal, 2020). Many agricultural regions are experiencing stagnating productivity, deteriorating natural resources, and increasing production costs. At the same time, climate change has emerged as a major threat to agricultural sustainability, with rising temperatures, erratic rainfall patterns, frequent droughts, floods, heat waves, and emerging pest and disease outbreaks affecting crop production and farm incomes. These challenges underscore the urgent need for a new agricultural

paradigm that can simultaneously enhance productivity, profitability, resilience, and environmental sustainability. In this context, regenerative agriculture and smart farming have gained considerable attention as complementary approaches for sustainable agricultural transformation. Regenerative agriculture focuses on restoring ecosystem functions through conservation agriculture, crop diversification, residue recycling, integrated nutrient management, agroforestry, and enhanced soil biological activity (Rhodes, 2017; Schreefel *et al.*, 2020). Concurrently, smart farming harnesses emerging technologies such as sensors, drones, artificial intelligence, machine learning, robotics, remote sensing, and big-data analytics to improve precision, resource-use efficiency, and farm decision-making (Wolfert *et al.*, 2017; Liakos *et al.*, 2018). The convergence of these ecological and technological innovations offers a promising framework for next-generation agriculture, capable of delivering higher productivity, improved resource efficiency, enhanced climate resilience, greater farmer profitability, and long-term sustainability of food systems in India and beyond.

The Need for Next-Generation Agriculture in India

India supports nearly one-fifth of the global population while possessing only a small share of the world's land and freshwater resources. Increasing pressure on natural resources has led to declining factor productivity in several intensive production systems. Soil organic carbon levels remain low in many agricultural regions, reducing nutrient-use efficiency and resilience to climatic stresses.

Groundwater depletion has become particularly severe in north-western India, where intensive rice–wheat cultivation dominates agricultural landscapes. Simultaneously, agricultural greenhouse gas emissions continue to rise due to inefficient fertilizer use, residue burning, and methane emissions from rice cultivation and livestock systems (Sapkota *et al.*, 2019).

Meeting future food demand while conserving natural resources requires a shift from input-intensive production models toward integrated systems that combine ecological sustainability with technological innovation. Regenerative-smart agriculture provides such an opportunity.

Healthy Soil, Healthy Crops, Prosperous Farmers: The Promise of Regenerative Agriculture

Regenerative agriculture is founded on the principle that long-term productivity depends upon healthy and resilient agroecosystems. Unlike conventional agriculture, which often emphasizes maximizing yields through external inputs, regenerative systems seek to enhance natural biological processes.

Key regenerative practices include conservation tillage, cover cropping, crop diversification, agroforestry, integrated crop-livestock systems, residue retention, and integrated nutrient management (Rhodes, 2017). These practices contribute to improved soil structure, increased soil organic matter, enhanced nutrient cycling, and greater biological activity.

Soil health represents the cornerstone of regenerative agriculture. Healthy soils improve water infiltration, nutrient retention, and root development while reducing erosion and land degradation. According to Lal (2020), restoring soil organic carbon not only improves agricultural productivity but also contributes significantly to climate change mitigation through carbon sequestration.

Crop diversification further strengthens resilience by reducing pest pressure, enhancing biodiversity, and improving resource-use efficiency. Agroforestry systems provide additional

ecological benefits through carbon storage, microclimate regulation, and diversified income sources.

Smart Farming Technologies for Sustainable Intensification

Smart farming integrates advanced digital technologies with agricultural management to enhance productivity, profitability, resource-use efficiency, and environmental sustainability. As agriculture faces increasing challenges from climate change, labour shortages, resource degradation, and rising input costs, smart farming offers innovative solutions for achieving sustainable intensification—producing more from existing farmland while minimizing environmental impacts.

Precision agriculture forms the foundation of smart farming by enabling site-specific crop management through GPS-guided machinery, geographic information systems (GIS), satellite imagery, drones, and variable-rate technologies. These tools allow farmers to apply seeds, fertilizers, pesticides, and irrigation water according to the specific needs of different field zones, thereby reducing input wastage and improving crop performance (Gebbers & Adamchuk, 2010). Such precision management not only enhances productivity but also lowers production costs and environmental pollution.

Artificial intelligence (AI), machine learning, and big-data analytics are increasingly being used to support decision-making in agriculture. These technologies can analyze vast amounts of information from weather stations, soil sensors, satellite images, and historical farm records to predict yields, diagnose diseases, forecast pest outbreaks, and recommend optimal management practices (Liakos *et al.*, 2018). Remote sensing technologies and unmanned aerial vehicles (UAVs) provide real-time monitoring of crop health, nutrient deficiencies, weed infestations, and moisture stress, enabling timely and targeted interventions (Zhang & Kovacs, 2012).

Furthermore, Internet of Things (IoT)-based sensors continuously monitor soil moisture, nutrient status, temperature, and microclimatic conditions, facilitating efficient irrigation and nutrient management. The integration of these technologies enhances resource-use efficiency, reduces production risks, strengthens climate resilience, and supports the transition toward sustainable, data-driven, and environmentally responsible agricultural systems.

Nature-Based Farming Powered by Smart Technologies

The integration of regenerative agriculture with smart farming technologies represents a transformative approach to sustainable agricultural development. While regenerative agriculture focuses on restoring soil health, enhancing biodiversity, improving nutrient cycling, and strengthening ecosystem resilience, smart technologies provide the precision, monitoring, and decision-support capabilities needed to optimize these ecological processes. Together, they create a powerful framework for improving productivity, profitability, and environmental sustainability.

Advanced digital tools such as soil sensors, Internet of Things (IoT) devices, drones, satellite imagery, and remote sensing technologies enable continuous monitoring of soil moisture, organic carbon, nutrient availability, crop health, and environmental conditions. These technologies generate real-time data that help farmers make informed decisions regarding irrigation, nutrient management, residue recycling, cover cropping, and crop diversification. For instance, drone-based imaging can assess vegetation vigour, monitor cover crop performance, and detect nutrient deficiencies or pest infestations at an early stage. Similarly, artificial intelligence and machine-learning algorithms can analyse large datasets to recommend optimal crop rotations, site-specific nutrient applications, and climate-responsive management practices.

Precision nutrient management complements regenerative farming by improving nutrient-use efficiency and minimizing fertilizer losses, thereby reducing production costs and environmental pollution. Smart irrigation systems further enhance water-use efficiency by delivering water according to crop demand and soil conditions. By combining ecological restoration with digital innovation, nature-based farming powered by smart technologies enables farmers to produce more with fewer resources while building resilient, climate-smart, and sustainable agricultural systems for the future.

Integrated Farming Systems: The Cornerstone of Next-Generation Agriculture

Integrated Farming Systems (IFS) represent one of the most effective pathways for operationalizing the principles of next-generation agriculture by combining ecological sustainability with technological innovation. An integrated farming approach links crops, livestock, fisheries, horticulture, agroforestry, mushroom cultivation, beekeeping, and other complementary enterprises into a synergistic production system where the outputs of one component serve as inputs for another (**Fig. 1**). Such resource recycling improves productivity, profitability, nutrient-use efficiency, and environmental sustainability while reducing dependence on external inputs.



Fig. 1. Integrated Farming Model for Regenerative-Smart Agriculture

From a regenerative agriculture perspective, integrated farming strengthens nutrient cycling, enhances soil organic matter, improves biodiversity, and promotes ecosystem resilience. Livestock manure, crop residues, compost, vermicompost, and biofertilizers contribute to soil health restoration and carbon sequestration, reducing reliance on synthetic fertilizers. Diversification

through multiple enterprises also minimizes production risks, improves farm resilience to climate variability, and provides year-round income and employment opportunities for farming households.

Smart farming technologies further enhance the efficiency and effectiveness of integrated farming systems. Internet of Things (IoT)-based sensors can monitor soil moisture, nutrient status, livestock health, water quality in fish ponds, and environmental conditions in real time. Artificial intelligence, remote sensing, drones, and digital advisory platforms enable precise management of crops and allied enterprises, facilitating data-driven decision-making and optimal resource allocation. Precision irrigation, automated feeding systems, climate-controlled production units, and digital market platforms can significantly improve productivity and profitability.

In the Indian context, where small and fragmented landholdings dominate agricultural landscapes, integrated farming offers a practical strategy for enhancing resource-use efficiency, reducing production costs, improving nutritional security, and increasing farmers' income. By combining regenerative principles with digital technologies, Integrated Farming Systems can serve as a cornerstone of climate-resilient, carbon-smart, and economically viable agriculture. Such systems embody the essence of next-generation agriculture by creating circular, resource-efficient, and sustainable food production systems capable of addressing future challenges while ensuring long-term farmer prosperity.

Crop Diversification and Sustainable Intensification: Pathways to Resilient and Profitable Agriculture

Crop diversification and sustainable intensification are fundamental pillars of next-generation agriculture, offering practical solutions to enhance productivity, profitability, resource-use efficiency, and climate resilience. For several decades, agricultural growth in many parts of India has been driven by intensive monocropping systems, particularly the rice–wheat production system. While these systems contributed significantly to food security, their long-term sustainability has been challenged by declining soil fertility, groundwater depletion, nutrient imbalances, pest outbreaks, biodiversity loss, and stagnating crop productivity.

Crop diversification involves the inclusion of a wider range of crops such as pulses, oilseeds, millets, fodder crops, vegetables, fruits, and agroforestry species within farming systems. Diversified cropping systems improve soil health by enhancing organic matter accumulation, promoting beneficial microbial activity, and improving nutrient cycling. Legume-based crop rotations contribute biologically fixed nitrogen, reducing dependence on synthetic fertilizers and lowering production costs. Diversification also interrupts pest and disease cycles, reduces production risks, and enhances resilience against climatic uncertainties such as droughts, floods, and temperature extremes.

Sustainable intensification complements diversification by increasing productivity per unit of land, water, energy, and other inputs without compromising environmental quality. Rather than relying solely on greater input use, sustainable intensification focuses on improving resource-use efficiency through conservation agriculture, precision nutrient management, micro-irrigation, improved crop varieties, integrated pest management, and digital decision-support systems. Smart farming technologies, including remote sensing, drones, artificial intelligence, and IoT-enabled sensors, further strengthen these approaches by enabling site-specific crop management and real-time monitoring of crop performance.

In the context of regenerative agriculture, diversified and intensified cropping systems enhance biodiversity, improve ecosystem services, increase carbon sequestration, and strengthen agroecosystem resilience. Diversified systems also provide multiple income streams, improve nutritional security, and create employment opportunities for rural households. By integrating crop diversification with sustainable intensification and smart farming technologies, farmers can achieve higher productivity and profitability while conserving natural resources and reducing environmental footprints.

For India, where shrinking landholdings and increasing climatic variability pose serious challenges, diversified and efficiently managed farming systems offer a viable pathway toward sustainable food production and farmer prosperity. Therefore, crop diversification and sustainable intensification should be viewed as essential components of next-generation agriculture, capable of balancing food security objectives with ecological sustainability and long-term agricultural resilience.

Weather-Proof Farming for Better Harvests

Climate change poses one of the greatest threats to Indian agriculture. Rising temperatures, erratic rainfall patterns, and increasing frequency of extreme weather events threaten crop yields and rural livelihoods. Regenerative agriculture contributes to climate change mitigation through increased carbon sequestration in soils and biomass. Soil carbon sequestration has been recognized as one of the most cost-effective biological approaches for removing atmospheric carbon dioxide (Paustian *et al.*, 2019). Conservation tillage, residue retention, cover cropping, and agroforestry can significantly enhance soil carbon stocks. At the same time, smart farming technologies improve climate adaptation. Weather forecasting systems, remote sensing platforms, and AI-based predictive models provide early warning of climatic risks, enabling timely management decisions. Precision irrigation technologies reduce water consumption and improve crop performance under water-limited conditions. Sapkota *et al.* (2019) demonstrated that climate-smart agricultural technologies in India offer significant potential for reducing greenhouse gas emissions while maintaining productivity and profitability.

Soil Health and Carbon: Twin Pillars of Sustainable Agriculture

The restoration and maintenance of soil health are fundamental to achieving long-term agricultural sustainability, food security, and environmental resilience. However, decades of intensive cultivation, excessive tillage, residue burning, nutrient imbalances, and soil erosion have led to declining soil fertility and productivity across many agricultural regions. Regenerative agriculture addresses these challenges by promoting practices such as conservation tillage, crop residue retention, cover cropping, crop diversification, organic amendments, and integrated nutrient management. These practices enhance soil biological activity, increase soil organic matter, and improve overall soil functioning.

Soil organic carbon serves as a key indicator of soil health, influencing nutrient availability, aggregate stability, water-holding capacity, root growth, and microbial diversity (Schreefel *et al.*, 2020). Higher carbon levels not only improve crop productivity but also contribute to climate change mitigation by sequestering atmospheric carbon dioxide. Recent advances in digital agriculture, including remote sensing, soil sensors, geographic information systems, and carbon-monitoring platforms, enable accurate assessment and verification of soil carbon dynamics. As highlighted by Smith *et al.*, (2020), reliable monitoring systems are essential for measuring carbon

sequestration and supporting emerging carbon-credit mechanisms. Integrating regenerative practices with digital soil-health monitoring can accelerate the development of productive, climate-resilient, and carbon-positive agricultural systems.

Biodiversity: The Hidden Strength of Farming

Agricultural biodiversity provides essential ecosystem services, including nutrient cycling, pollination, pest regulation, and soil formation. However, intensive monoculture systems often reduce biodiversity and ecosystem resilience. Regenerative agriculture promotes biodiversity through diversified cropping systems, agroforestry, habitat conservation, and reduced chemical dependence (Schreefel *et al.*, 2020). Enhanced biodiversity strengthens ecosystem stability and improves resilience to environmental disturbances. Smart technologies further support biodiversity conservation through automated monitoring systems, image recognition tools, and remote sensing applications. Such technologies enable continuous assessment of ecosystem health and facilitate evidence-based management decisions.

Improving farmers' income and quality of life.

Sustainable agricultural transitions must remain economically viable for farmers. Regenerative-smart agriculture offers substantial opportunities for reducing production costs while improving profitability. Precision input management reduces expenditure on fertilizers, pesticides, water, and fuel. Improved soil health decreases dependence on external inputs over time. Enhanced resilience reduces production risks associated with climatic variability. The integration of digital technologies also improves market access, supply-chain efficiency, and farm-level decision-making. Furthermore, emerging carbon markets and ecosystem-service payments may provide additional income streams for farmers adopting regenerative practices. Long-term evidence suggests that sustainable intensification strategies can simultaneously enhance productivity, profitability, and environmental outcomes (Gebbers & Adamchuk, 2010).

Challenges and Future Directions

Despite its immense potential, the large-scale adoption of regenerative-smart agriculture faces several technological, economic, institutional, and social challenges. The high initial cost of precision farming tools, sensors, drones, automated irrigation systems, and digital platforms often limits their accessibility, particularly for small and marginal farmers who constitute the majority of India's farming community. Fragmented landholdings, inadequate rural digital infrastructure, poor internet connectivity, and limited access to credit further constrain the adoption of advanced technologies. Additionally, low levels of digital literacy, insufficient awareness about regenerative practices, and weak last-mile extension services hinder the effective dissemination and implementation of these innovations. The absence of standardized protocols for measuring soil health improvements, carbon sequestration, and ecosystem services also restricts the development of reliable incentive mechanisms.

Future research should prioritize the development of affordable, user-friendly, and scalable precision agriculture technologies tailored to smallholder farming systems. Greater emphasis is needed on improving carbon accounting frameworks, integrating artificial intelligence with regenerative farming models, and generating location-specific evidence across diverse agroecological regions. Strengthening digital advisory systems and real-time decision-support tools will further enhance adoption.

Policy interventions will play a pivotal role in accelerating this transition. Investments in rural digital infrastructure, farmer capacity building, custom hiring centres, carbon credit mechanisms,

climate-smart incentives, and public-private partnerships are essential. A coordinated approach involving research institutions, extension agencies, private enterprises, and farmer organizations will be crucial for mainstreaming regenerative-smart agriculture and achieving sustainable, resilient, and profitable food systems.

Future Pathways for Next-Generation Agriculture

The future of agriculture will be shaped by its ability to simultaneously meet the growing demand for food, nutrition, fibre, and bio-based products while conserving natural resources and mitigating climate change. As agricultural systems face increasing pressures from resource degradation, climate variability, labour shortages, and market uncertainties, the integration of regenerative principles with smart farming technologies offers a transformative pathway toward sustainable and resilient food systems. The transition to next-generation agriculture requires a holistic approach that combines ecological restoration, technological innovation, institutional support, and farmer-centric development strategies.

A key future pathway lies in restoring soil health as the foundation of agricultural sustainability. Enhancing soil organic carbon through conservation agriculture, crop residue recycling, cover cropping, agroforestry, and integrated nutrient management will improve productivity, water-use efficiency, biodiversity, and climate resilience. Simultaneously, digital technologies such as soil sensors, remote sensing, geographic information systems, and carbon-monitoring platforms will enable real-time assessment of soil health and ecosystem services.

The widespread adoption of artificial intelligence, machine learning, drones, robotics, and Internet of Things (IoT)-based technologies will further transform farm management by enabling precision agriculture and data-driven decision-making. These technologies can optimize resource utilization, reduce input costs, minimize environmental footprints, and improve farm profitability. Future agricultural systems will increasingly rely on predictive analytics, automated operations, and digital advisory services tailored to local agroecological conditions.

Integrated Farming Systems (IFS), crop diversification, and sustainable intensification will play a critical role in enhancing farm resilience and income security. Diversified production systems integrating crops, livestock, fisheries, horticulture, agroforestry, and value-added enterprises can create circular bio-economies that maximize resource recycling and reduce dependence on external inputs. Such systems are particularly relevant for smallholder farmers who need multiple income streams and greater protection against climatic and market risks.

Climate-smart agriculture must become a central component of future agricultural strategies. The development and dissemination of stress-tolerant crop varieties, precision water management technologies, carbon-smart farming practices, and weather-based advisory services will help farmers adapt to changing climatic conditions while contributing to greenhouse gas mitigation. Emerging carbon markets and ecosystem service payments can provide additional incentives for adopting regenerative practices and improving environmental stewardship.

Strengthening agricultural research, education, and extension systems will be essential for accelerating this transformation. Future research should focus on developing affordable and scalable technologies, improving carbon accounting methodologies, integrating biological and digital innovations, and generating location-specific solutions for diverse farming systems. Agricultural universities, research institutions, start-ups, private enterprises, and extension

agencies must work collaboratively to create innovation ecosystems that support knowledge transfer and technology adoption.

Policy reforms will be equally important. Investments in rural digital infrastructure, custom hiring centers, climate-resilient technologies, farmer producer organizations (FPOs), carbon-credit mechanisms, and public-private partnerships can facilitate widespread adoption of regenerative-smart agriculture. Incentive structures should reward resource conservation, carbon sequestration, biodiversity enhancement, and sustainable land management practices.

Looking ahead to India's centenary year in 2047, next-generation agriculture must move beyond the singular goal of maximizing production toward creating productive, profitable, climate-resilient, resource-efficient, and environmentally sustainable farming systems. By effectively bridging regenerative agriculture with smart farming technologies, India has the opportunity to lead a global agricultural transformation that ensures food and nutritional security, enhances farmer prosperity, restores ecological health, and contributes to a sustainable future for generations to come.

Epilogue

Agriculture stands at a defining crossroads. The remarkable gains in food production achieved during the Green Revolution era have ensured food security for billions, yet they have also exposed the limitations of resource-intensive farming systems. Soil degradation, biodiversity loss, water scarcity, climate change, and rising production costs underscore the urgent need for a new agricultural paradigm that balances productivity with ecological sustainability.

The convergence of regenerative agriculture and smart farming offers a transformative pathway toward such a future. Regenerative principles restore the biological foundations of agriculture by rebuilding soil health, enhancing biodiversity, strengthening ecosystem services, and sequestering carbon. Smart farming technologies, powered by digital innovations, artificial intelligence, remote sensing, robotics, and precision management, enable farmers to make informed decisions that maximize efficiency while minimizing environmental impacts. Together, these approaches represent the essence of next-generation agriculture—an integrated system where ecological wisdom and technological intelligence work in harmony.

For India, this transition is particularly significant. As the nation moves toward its centenary in 2047, the challenge is not merely to produce more food but to produce it sustainably, profitably, and resiliently. The future agricultural landscape must support healthy soils, efficient water use, climate-resilient crops, thriving biodiversity, and prosperous farming communities. Achieving this vision will require coordinated efforts involving researchers, policymakers, extension agencies, private-sector innovators, and farmers themselves.

The success of next-generation agriculture will depend on fostering innovation ecosystems that make advanced technologies affordable and accessible while promoting regenerative practices suited to diverse agroecological conditions. Investments in research, capacity building, digital infrastructure, climate-smart policies, and farmer-centric extension services will be essential to accelerate adoption at scale.

Ultimately, the future of agriculture lies not in choosing between nature and technology, but in intelligently combining both. Healthy soils enriched through regenerative practices, guided by data-driven smart technologies, can create productive, profitable, and environmentally sustainable

farming systems. By bridging regenerative principles with smart farming, agriculture can evolve from a sector focused primarily on production to one that simultaneously nurtures ecosystems, strengthens rural livelihoods, combats climate change, and secures food and nutritional security for future generations.

The journey toward next-generation agriculture has already begun. The challenge before us is to ensure that this transformation is inclusive, science-based, and farmer-cantered, enabling agriculture to remain a cornerstone of sustainable development and human well-being in the decades ahead.

Conclusion

The future sustainability of Indian agriculture depends upon its ability to simultaneously increase productivity, enhance resilience, and conserve natural resources. Regenerative agriculture provides ecological solutions through soil restoration, biodiversity enhancement, and carbon sequestration, while smart farming offers technological solutions through precision management and data-driven decision-making. Their integration represents a transformative pathway toward next-generation agriculture capable of addressing the challenges of food security, climate change, and environmental sustainability. By bridging regenerative principles with smart farming technologies, India can build resilient, productive, and sustainable food systems that support both farmer prosperity and ecological well-being.

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PATTERN RECOGNITION RECEPTORS (PRRS): EVOLUTION, STRUCTURE, AND ENGINEERING NEW IMMUNITY

Zainab Rashid¹, Hinna Javid¹, Dasari Meghanath²

Aflaq Hamid² and Sumiah Wani^{2*}

¹Ph.D. Scholar, Division of Plant Pathology, Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

²DNA fingerprinting and advanced plant virology laboratory, AICRP-NSP, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

*Corresponding Email: sumiahwani@gmail.com

Abstract

Pattern Recognition Receptors (PRRs) are cell-surface immune receptors that constitute the first line of defense in plants by recognizing conserved pathogen-associated molecular patterns (PAMPs) and damage-associated molecular patterns (DAMPs). These receptors initiate pattern-triggered immunity (PTI), a broad-spectrum defense response that restricts microbial colonization. PRRs have evolved remarkable structural diversity, including leucine-rich repeat receptor kinases (LRR-RKs), leucine-rich repeat receptor proteins (LRR-RPs), and lysin motif receptors (LysM-RKs), enabling recognition of bacterial, fungal, and oomycete pathogens. Advances in structural biology have clarified ligand binding and receptor complex assembly with co-receptors such as BAK1 and CERK1. These discoveries have facilitated engineering approaches, including interspecies transfer, domain swapping, and genome editing, to generate crops with enhanced resistance. This review summarizes the evolution, structural organization, signaling mechanisms, and engineering of PRRs, highlighting their significance in sustainable agriculture and future crop protection strategies.

Keywords

Pattern Recognition Receptors; Pattern-Triggered Immunity; Leucine-Rich Repeat Receptors; LysM Receptors; Disease Resistance Engineering.

Introduction

Plants are constantly exposed to a wide variety of microorganisms, including bacteria, fungi, oomycetes, viruses, and nematodes. Because plants lack specialized immune cells and adaptive immunity, each cell must independently detect invading organisms and activate defense responses. This protection is mediated by a highly sophisticated innate immune system.

The modern understanding of plant immunity was formalized by Jones and Dangl (2006), who proposed a two-tiered immune model. The first layer, pattern-triggered immunity (PTI), is initiated when cell-surface Pattern Recognition Receptors (PRRs) detect conserved microbial molecules known as pathogen-associated molecular patterns (PAMPs) or microbe-associated molecular patterns (MAMPs). Examples include bacterial flagellin, elongation factor Tu (EF-Tu), fungal chitin, and oomycete β -glucans. The second layer, effector-triggered immunity (ETI), is activated when intracellular nucleotide-binding leucine-rich repeat receptors (NLRs) recognize pathogen effectors.

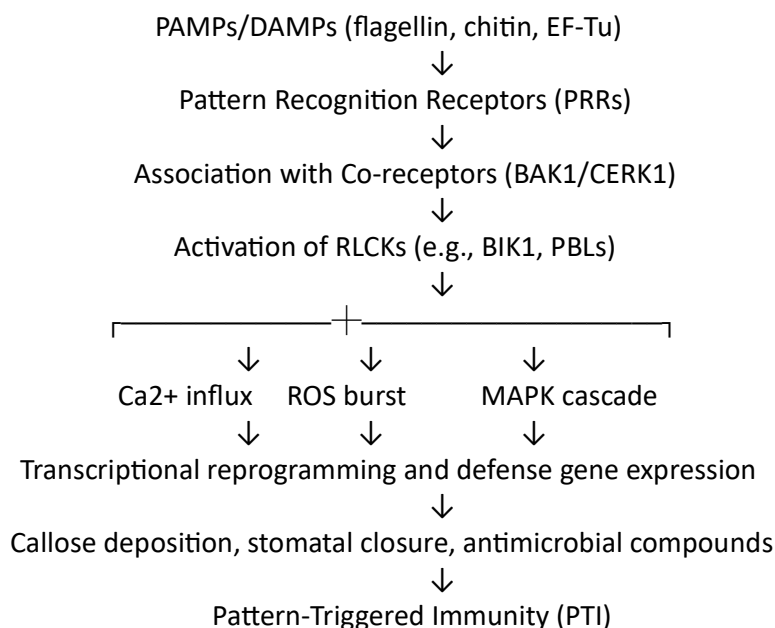
PRRs are strategically positioned on the plasma membrane to monitor the extracellular environment. Upon ligand perception, they recruit co-receptors such as BAK1 (BRI1-Associated

Kinase 1) or CERK1 (Chitin Elicitor Receptor Kinase 1), triggering phosphorylation cascades, calcium influx, reactive oxygen species (ROS) generation, mitogen-activated protein kinase (MAPK) activation, and transcriptional reprogramming.

The discovery of PRRs has revolutionized plant pathology and crop biotechnology. Notably, transfer of Arabidopsis EFR (EF-Tu Receptor) into tomato, rice, wheat, and potato has conferred broad-spectrum bacterial resistance. This demonstrates the potential of PRRs as powerful tools for engineering durable and environmentally sustainable disease resistance.

This review examines the evolution, structure, signaling mechanisms, and engineering applications of PRRs, with emphasis on their role in developing next-generation crop immunity.

Figure 1. Model of PRR-Mediated Immunity



Historical Perspective and Discovery of PRRs

The concept of inducible plant defense emerged gradually through studies demonstrating that plants can perceive conserved molecules from microbes and rapidly activate defense responses. In the early 1990s, several microbial elicitors were identified, but the molecular basis of their perception remained unclear.

A landmark discovery was made by Felix and colleagues in 1999, who showed that a highly conserved 22-amino acid peptide derived from bacterial flagellin, termed flg22, was sufficient to induce alkalinization, oxidative burst, and defense gene expression in *Arabidopsis thaliana*. This study provided the first compelling evidence that plants recognize invariant microbial signatures rather than pathogen-specific molecules.

In 2000, Laurent Gómez-Gómez and Thomas Boller cloned the first bona fide plant PRR, FLS2, from *Arabidopsis*. FLS2 encodes a leucine-rich repeat receptor kinase (LRR-RK) that specifically detects flg22 and initiates immune signaling.

Subsequent breakthroughs led to the identification of numerous PRRs, including:

- EFR, which recognizes the bacterial elongation factor Tu peptide elf18.

- CERK1 and LYK5, which mediate chitin recognition.
- CEBiP in rice.
- PEPR1 and PEPR2, which detect endogenous danger peptides.
- RLP23, which recognizes necrosis-inducing proteins.

In parallel, animal immunology revealed Toll-like receptors, highlighting a universal biological strategy in which hosts use germline-encoded receptors to detect conserved features of microbes. These discoveries established PRRs as fundamental components of innate immunity and laid the foundation for modern research on plant–microbe interactions.

Evolution of Pattern Recognition Receptors

• Origins of Innate Immune Recognition

Innate immune recognition predates the evolutionary divergence of plants and animals. Although plant PRRs and animal Toll-like receptors evolved independently, both systems perform analogous functions by detecting conserved molecular signatures and initiating rapid defense responses. This represents a striking example of convergent evolution.

• Expansion of Receptor Families in Plants

Plant genomes encode exceptionally large families of receptor-like kinases (RLKs) and receptor-like proteins (RLPs). For example:

- *Arabidopsis thaliana* contains approximately 610 RLKs and 57 RLPs.
- *Oryza sativa* encodes more than 1,100 RLKs.
- *Triticum aestivum* possesses thousands of receptor-like genes due to its hexaploid genome.

The extensive expansion of these families reflects strong selective pressure imposed by diverse and rapidly evolving pathogens.

• Mechanisms Driving PRR Evolution

PRR diversity has arisen through several molecular processes:

1. Gene duplication followed by functional divergence.
2. Unequal crossing-over and recombination.
3. Domain shuffling and exon swapping.
4. Positive selection in ligand-binding regions.
5. Polyploidization and genome duplication.

These processes generate receptors with novel recognition specificities and improved signaling capacities.

• Diversification of Extracellular Domains

The extracellular domains of PRRs have diversified to detect a broad range of ligands. Major domain types include:

- Leucine-rich repeats (LRRs)
- Lysin motifs (LysM)
- Lectin domains
- Wall-associated kinase domains
- Epidermal growth factor-like domains

Each domain architecture confers distinct biochemical recognition properties.

- **Co-evolution with Pathogens**

Pathogens secrete effectors that suppress pattern-triggered immunity, while plants evolve new receptors or modify existing ones to restore recognition. This ongoing host–pathogen arms race drives rapid diversification of PRR genes and contributes to the dynamic nature of immune receptor evolution.

Structural Organization of PRRs

Pattern Recognition Receptors are transmembrane proteins designed to detect extracellular ligands and convert recognition events into intracellular signaling.

Extracellular Domain (ECD)

The extracellular domain is responsible for ligand binding. Its structure determines the spectrum and specificity of recognition. Common motifs include LRRs and LysM domains.

Transmembrane Domain

A single hydrophobic α -helix anchors the receptor in the plasma membrane and connects the extracellular sensing module to the intracellular signaling region.

Intracellular Kinase Domain

Most receptor-like kinases possess a serine/threonine kinase domain that phosphorylates downstream substrates and propagates immune signals.

Receptor-Like Proteins (RLPs)

RLPs lack a kinase domain and depend on accessory proteins such as SOBIR1 and BAK1 for signal transduction.

Modular Architecture and Functional Flexibility

The modular nature of PRRs allows natural recombination and artificial engineering through domain swapping, enabling the creation of receptors with customized recognition and signaling properties.

Table 1. Major Classes of Plant PRRs

PRR Class	Structural Domain	Representative Receptors	Recognized Ligands
LRR-RK	Leucine-rich repeats + kinase	FLS2, EFR, PEPR1	flg22, EF-Tu, Pep peptides
LRR-RP	Leucine-rich repeats, no kinase	RLP23, Cf proteins	NLPs, fungal proteins
LysM-RK	LysM motifs + kinase	CERK1, LYK5	Chitin, peptidoglycan
LysM-RP	LysM motifs, no kinase	CEBiP	Chitin oligomers
Lectin RK	Lectin domain	Lec RKs	Extracellular ATP, carbohydrates
WAK	Wall-associated kinase	WAK1	Oligogalacturonides

Major Pattern Recognition Receptors

FLS2 (Flagellin-Sensing 2)

FLS2 is the best-characterized plant PRR and serves as the paradigm for understanding cell-surface immune recognition. It is a leucine-rich repeat receptor kinase (LRR-RK) from *Arabidopsis thaliana* that specifically recognizes the highly conserved 22-amino acid peptide flg22 derived from

bacterial flagellin. Ligand binding induces rapid heterodimerization with the co-receptor BAK1, followed by phosphorylation of downstream kinases such as BIK1 and activation of robust immune responses.

EFR (EF-Tu Receptor)

EFR recognizes the elf18 peptide derived from bacterial elongation factor Tu. EFR is naturally restricted to members of the Brassicaceae family but remains fully functional when transferred to unrelated crops, making it one of the most successful examples of PRR-based engineering for broad-spectrum bacterial resistance.

CERK1 and LYK5

LYK5 binds fungal chitin with very high affinity and recruits CERK1 to form an active signaling complex. Together, these receptors play a central role in antifungal immunity.

CEBiP and OsCERK1

In *Oryza sativa*, CEBiP is a LysM receptor protein that lacks an intracellular kinase domain. It binds chitin oligomers and forms a signaling complex with OsCERK1.

PEPR1 and PEPR2

PEPR1 and PEPR2 recognize endogenous Plant Elicitor Peptides (Peps) released during tissue damage, thereby amplifying immune responses and linking damage sensing to pathogen defense.

RLP23

RLP23 detects conserved motifs from necrosis- and ethylene-inducing peptide-like proteins (NLPs), which are secreted by fungi, bacteria, and oomycetes.

WAK1

WAK1 binds oligogalacturonides released from degraded plant cell walls and functions as an important receptor for damage-associated molecular patterns.

Ligands Recognized by PRRs

PRRs recognize both microbial molecules and endogenous host-derived signals.

Pathogen-Associated and Microbe-Associated Molecular Patterns (PAMPs/MAMPs)

These are evolutionarily conserved molecules essential for microbial survival:

- Flagellin (flg22)
- Elongation factor Tu (elf18)
- Chitin
- Peptidoglycan
- Lipopolysaccharides
- β -glucans
- NLP-derived peptides

Damage-Associated Molecular Patterns (DAMPs)

These endogenous molecules are released upon tissue injury or pathogen attack:

- Plant Elicitor Peptides (Peps)
- Oligogalacturonides (OGs)
- Extracellular ATP (eATP)
- Extracellular NAD⁺ (eNAD⁺)

Importance of Ligand Recognition

The recognition of conserved ligands enables plants to detect entire classes of pathogens rather than individual strains, making PRR-mediated immunity inherently broad-spectrum and evolutionarily durable.

Table 2. Representative PRRs and Their Ligands

Receptor	Species	Ligand	Pathogen Type
FLS2	Arabidopsis	flg22	Bacteria
EFR	Arabidopsis	elf18	Bacteria
LYK5/CERK1	Arabidopsis	Chitin	Fungi
CEBiP/OsCERK1	Rice	Chitin	Fungi
PEPR1/PEPR2	Arabidopsis	Pep peptides	Damage signals
WAK1	Arabidopsis	Oligogalacturonides	Cell wall damage
RLP23	Arabidopsis	NLP peptides	Fungi and oomycetes

Molecular Mechanism of PRR Activation

Pattern Recognition Receptors (PRRs) are maintained at the plasma membrane in inactive conformations or in preassembled complexes. Recognition of a ligand induces rapid conformational rearrangements that promote receptor oligomerization and activation of intracellular signaling.

Ligand Binding and Receptor Complex Formation

The extracellular domain of a PRR specifically binds its cognate ligand. This interaction either stabilizes a pre-existing receptor complex or induces the formation of a new heteromeric complex with co-receptors.

For example:

- FLS2 binds flg22 and recruits BAK1.
- EFR recognizes elf18 and similarly associates with BAK1.
- LYK5 binds chitin and recruits CERK1.
- Receptor-like proteins such as RLP23 depend on SOBIR1 and BAK1 for signaling.

Phosphorylation Cascades

Following receptor complex formation, reciprocal transphosphorylation activates the kinase domains. Activated receptors phosphorylate receptor-like cytoplasmic kinases (RLCKs), particularly BIK1 and related PBL proteins.

Calcium Signaling

PRR activation stimulates opening of calcium-permeable channels, causing a rapid increase in cytosolic Ca^{2+} concentration. Calcium acts as a second messenger and activates calmodulins, calcium-dependent protein kinases (CDPKs), and other signaling proteins.

Reactive Oxygen Species Production

BIK1 phosphorylates RBOHD, leading to a rapid oxidative burst in the apoplast. ROS function directly as antimicrobial molecules and as secondary messengers.

MAPK Cascades

Mitogen-activated protein kinase cascades, particularly MPK3, MPK4, and MPK6, relay signals to the nucleus and regulate defense-related transcription factors such as WRKY proteins.

Hormonal and Transcriptional Reprogramming

PRR signaling influences salicylic acid, ethylene, and jasmonic acid pathways and induces large-scale changes in gene expression, including activation of pathogenesis-related (PR) genes.

Pattern-Triggered Immunity Responses

Pattern-triggered immunity (PTI) results in a coordinated set of physiological and biochemical defenses:

1. Rapid oxidative burst
2. Cytosolic calcium elevation
3. Stomatal closure
4. Callose deposition at the cell wall
5. Lignification and cell wall reinforcement
6. Production of phytoalexins and antimicrobial compounds
7. Expression of defense-related genes
8. Restriction of pathogen colonization and spread

These responses provide broad-spectrum resistance against many bacterial, fungal, and oomycete pathogens.

Structural Biology of PRRs

High-resolution structural studies using X-ray crystallography and cryo-electron microscopy have transformed our understanding of ligand recognition and receptor activation.

FLS2–flg22–BAK1 Complex

The crystal structure solved by Yue Sun and colleagues showed that flg22 acts as a molecular bridge between FLS2 and BAK1, stabilizing the active receptor complex.

EFR–BAK1 Complex

EFR binds elf18 through a similar mechanism, illustrating a conserved mode of activation among LRR receptor kinases.

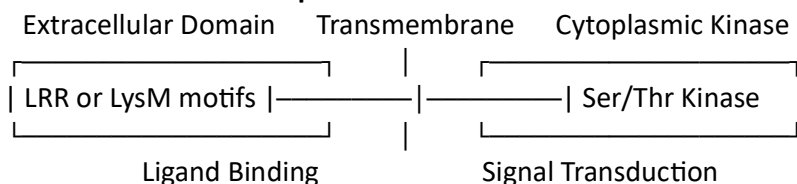
Chitin Recognition by LysM Receptors

LysM domains form carbohydrate-binding grooves that specifically recognize N-acetylglucosamine residues within chitin oligomers.

Importance for Engineering

Structural knowledge enables rational modification of ligand-binding surfaces and receptor interfaces, providing a foundation for designing PRRs with broadened or altered recognition capabilities.

Figure 2. General Architecture of a Receptor-Like Kinase

**Crosstalk Between Pattern-Triggered Immunity (PTI) and Effector-Triggered Immunity (ETI)**

For many years, PTI and ETI were considered two distinct and largely independent branches of plant immunity. PTI was viewed as the first layer of defense mediated by cell-surface Pattern

Recognition Receptors (PRRs), whereas ETI was regarded as a second, more robust response activated by intracellular nucleotide-binding leucine-rich repeat receptors (NLRs) that detect pathogen effectors. Recent studies have fundamentally revised this model and demonstrated that PTI and ETI are highly interconnected and mutually reinforcing.

Activation of PTI establishes a physiological state that enhances ETI responses, while ETI amplifies the outputs of PRR signaling, including reactive oxygen species (ROS) production, mitogen-activated protein kinase (MAPK) activation, and defense gene expression. For example, ETI can increase the abundance and activity of PRR-associated signaling components such as BIK1 and RBOHD. This synergistic interaction generates a more robust and durable immune response than either pathway alone.

The concept of mutual potentiation has important implications for crop improvement, suggesting that combining optimized PRRs with effective NLR genes may provide exceptionally strong and long-lasting disease resistance.

Engineering New Immunity Using PRRs

The modular organization and cross-species compatibility of PRRs make them highly attractive targets for engineering disease resistance.

Transgenic Transfer of PRRs

One of the most successful approaches is the transfer of PRR genes from one species to another. The Arabidopsis EFR receptor has been introduced into tomato, rice, wheat, potato, and citrus, where it conferred enhanced resistance to multiple bacterial pathogens. Because downstream signaling components are widely conserved, transferred PRRs can function efficiently in distantly related species.

Domain Swapping

Chimeric receptors can be created by combining the extracellular ligand-binding domain of one receptor with the intracellular kinase domain of another. A well-known example is the EFR: XA21 chimera, which couples the bacterial recognition capability of EFR with the strong signaling capacity of the rice XA21 kinase domain.

Directed Evolution and Site-Directed Mutagenesis

Targeted amino acid substitutions in ligand-binding domains can alter receptor specificity, improve affinity, and enhance immune responsiveness.

Genome Editing

CRISPR-Cas9 and related technologies enable precise manipulation of endogenous PRR loci, including promoter replacement, coding sequence optimization, and deletion of negative regulators.

Synthetic Biology

Emerging synthetic biology approaches aim to design entirely new receptors and signaling circuits with customized recognition properties.

Table 3. Strategies for Engineering PRR-Based Immunity

Strategy	Description	Example
Gene Transfer	Introduction of PRRs from other species	EFR in rice and tomato

Strategy	Description	Example
Domain Swapping	Construction of chimeric receptors	EFR: XA21
Promoter Engineering	Enhanced expression of PRRs	Strong constitutive or inducible promoters
CRISPR Editing	Modification of endogenous PRR genes	Promoter replacement, coding edits
Synthetic Biology	Design of novel receptors	Custom ligand-recognition modules

Successful Applications in Crop Improvement

Rice

Expression of EFR and manipulation of chitin receptors have improved resistance to bacterial blight and fungal diseases.

Tomato

EFR-transgenic tomato plants exhibit increased resistance to *Ralstonia solanacearum* and *Xanthomonas* species.

Wheat

Transferred PRRs enhance responsiveness to bacterial elicitors and strengthen basal immunity.

Citrus

EFR expression provides improved tolerance to citrus canker caused by *Xanthomonas citri*.

Potato

PRR-based engineering has increased resistance to bacterial wilt and soft rot pathogens.

These successes demonstrate that PRR signaling pathways are highly conserved and transferable across diverse crop species. Combining PRR engineering with inducible promoters, precise genome editing, and stacking with NLR genes offers promising solutions. The integration of genomics, structural biology, machine learning, and synthetic biology will likely transform PRR engineering into a cornerstone of modern crop improvement.

Conclusion

Pattern Recognition Receptors are fundamental components of plant innate immunity, acting as molecular sentinels that detect conserved microbial and endogenous danger signals. Their evolutionary diversification has produced a wide range of receptor architectures capable of recognizing bacteria, fungi, and oomycetes. Structural and mechanistic studies have revealed how PRRs bind ligands, recruit co-receptors, and activate signaling pathways that culminate in pattern-triggered immunity. The successful transfer and redesign of PRRs across crop species has demonstrated their immense potential for engineering broad-spectrum and durable disease resistance. As genome editing, structural biology, and synthetic biology continue to advance, PRR-based strategies are poised to play a central role in safeguarding global food security and promoting sustainable agriculture.

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PIGEON POX: AN EMERGING THREAT TO DOMESTIC AND FANCY PIGEONS

R. Suresh^{1*} and Ch. Srinija²

¹Assistant Professor, Veterinary Clinical Complex, College of Veterinary Science, PVNRTVU, Korutla, Telangana, India

²Post Graduate Scholar, VMD, PVNRTVU, Rajendranagar, Telangana, India

*Corresponding Email: sureshrasamalla@gmail.com

Abstract

Pigeon pox is a common viral disease of pigeons characterized by proliferative cutaneous lesions affecting non-feathered areas of the body. A juvenile pigeon was presented with multiple nodular, crusted lesions involving the periocular region, cere, and beak commissures, accompanied by reduced feed intake, mild depression, poor feather condition, and stunted growth. A presumptive diagnosis of cutaneous pigeon pox was established based on the characteristic clinical appearance and distribution of lesions, while differential diagnoses were excluded through clinical examination. The bird was managed with supportive therapy, topical wound care, vitamin supplementation, and appropriate management practices, resulting in progressive regression of lesions and complete clinical recovery. This case highlights the importance of recognising the characteristic clinical features of pigeon pox for early diagnosis and timely supportive management, which can significantly improve prognosis and minimise complications from secondary infections.

Keywords: Pigeon pox, Avipoxvirus, Cutaneous form, Pigeon, Clinical management, Case report.

Introduction

Pigeon pox is a widely distributed viral disease affecting domestic, racing, ornamental, and free-ranging pigeons worldwide. It is caused by pigeonpox virus (PPV), a host-specific member of the genus *Avipoxvirus* (family *Poxviridae*), and typically manifests as proliferative, wart-like cutaneous lesions on non-feathered regions such as the eyelids, cere, beak commissures, and legs. In some cases, the infection also produces diphtheritic plaques on the mucous membranes of the oral cavity, pharynx, and upper respiratory tract, resulting in the wet form of the disease (Tripathy & Reed, 2020). Although pigeon pox is often self-limiting, severe cases can lead to anorexia, reduced growth, impaired vision, respiratory compromise, secondary bacterial infections, decreased performance, and increased mortality, particularly among juvenile birds (Samour, 2016; Swayne *et al.*, 2020). The disease occurs more frequently in tropical and subtropical climates where vector populations, especially mosquitoes, remain abundant for extended periods. Young pigeons are especially vulnerable because of their developing immune system, inadequate acquired immunity, and greater susceptibility to environmental and management-related stressors (van Riper & Forrester, 2007).

Clinical Presentation

A juvenile pigeon was presented with multiple proliferative nodular lesions affecting the periocular region, cere, beak commissures, and adjacent unfeathered skin (Fig. 1). The lesions were yellowish-brown, crusted, and wart-like, causing partial closure of the eyelids. The bird showed reduced feed intake, mild depression, poor feather condition, and stunted growth.



Fig. 1& 2. Clinical presentation of a pigeon naturally affected with pigeon pox, showing characteristic proliferative, nodular, and crusted cutaneous lesions involving the periocular region, cere, and beak (dry form of pigeon pox).

The lesions were dry, proliferative and firmly attached to the underlying tissue, which is typical of the cutaneous (dry) form of pigeon pox. No diphtheritic plaques were observed within the oral cavity, and respiratory signs were absent at the time of examination.

Diagnosis

A presumptive diagnosis of cutaneous pigeon pox was made based on the bird's age and the presence of characteristic proliferative, crusted lesions on the non-feathered areas of the head and periocular region (Tripathy & Reed, 2020). Differential diagnoses included trichomoniasis, vitamin A deficiency, bacterial dermatitis, fungal dermatitis, traumatic wounds, and avian herpesvirus infection. However, the clinical presentation was most consistent with cutaneous pigeon pox (Swayne *et al.*, 2020). Confirmation may be achieved by histopathology demonstrating Bollinger bodies or by PCR, virus isolation, or electron microscopy (Manarolla *et al.*, 2010).

Treatment and Management

As no specific antiviral therapy is available for pigeon pox, treatment focused on supportive care and the prevention of secondary bacterial infections. The lesions were cleaned gently with diluted povidone-iodine solution, and topical antiseptic therapy was instituted to minimize bacterial contamination. Vitamin and mineral supplementation, particularly vitamin A, was recommended to enhance epithelial regeneration and immune competence.

The affected bird was isolated from the flock to prevent disease transmission. Adequate nutrition, clean drinking water, and reduction of environmental stress were ensured throughout the recovery period. In severe cases complicated by secondary bacterial infections, broad-spectrum antimicrobial therapy may be administered under veterinary supervision (Samour, 2016). Most uncomplicated cutaneous lesions regress gradually within two to four weeks, leaving minimal residual scarring. Early intervention helps prevent secondary complications and improves recovery.

Prevention and Control

Prevention remains the most effective strategy for controlling pigeon pox. Mosquito control is particularly important because blood-feeding insects serve as major mechanical vectors of

avipoxvirus transmission (Tripathy & Reed, 2020). Elimination of stagnant water sources, installation of insect screens, and maintenance of environmental hygiene significantly reduce disease incidence.

Additional preventive measures include:

- Quarantine of newly introduced birds.
- Avoidance of overcrowding.
- Regular cleaning and disinfection of lofts.
- Prompt removal of infected scabs and contaminated litter.
- Provision of balanced nutrition and vitamin supplementation.
- Vaccination of valuable breeding and racing pigeons in endemic regions.

Because avipoxviruses can survive for prolonged periods in dried scabs, proper sanitation is essential to interrupt environmental transmission (Swayne *et al.*, 2020).

Conclusion

Pigeon pox remains an important viral disease of pigeons and should be considered whenever proliferative nodular lesions are observed on non-feathered skin. The present case demonstrated the classical cutaneous form of pigeon pox characterised by periocular and beak lesions in a juvenile pigeon. Early clinical recognition, supportive care, isolation of affected birds, vector control, and good husbandry practices are essential for successful disease management and prevention. Increased awareness among pigeon owners and avian practitioners can significantly reduce the impact of this economically important disease.

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PLANT BIOSECURITY: PROTECTING CROPS FROM NEW DISEASES A MODERN APPROACH TO SAFEGUARDING AGRICULTURE AND FOOD SECURITY

Megha Asiwai, S. K. Goyal*, Shailesh Godika and Jitendra Singh

Department of Plant Pathology, Shree Karan Narendra Agriculture University, Jobner
Rajasthan 303 329

*Corresponding Email: skgoyal.skncoa@sknau.ac.in

Introduction

Agriculture is the backbone of food security and rural livelihoods across the world. However, crop production faces numerous challenges, among which plant diseases are one of the most destructive. Every year, fungal, bacterial, viral, and nematode diseases cause billions of dollars in crop losses, reducing both yield and quality. With globalization, climate change, increased international trade, and the movement of people and agricultural products, the risk of introducing new plant diseases has grown significantly.

This has made plant biosecurity one of the most important areas of modern plant pathology. Plant biosecurity refers to the measures and strategies used to prevent the introduction, establishment, and spread of harmful plant pests and diseases. Rather than simply treating diseases after they occur, biosecurity focuses on prevention, early detection, rapid response, and long-term management.

For farmers, plant biosecurity is not just a government responsibility; it is a practical approach that protects crops, improves productivity, reduces economic losses, and ensures sustainable agriculture. This article explains the concept of plant biosecurity, its importance, emerging threats, modern technologies, and practical measures that farmers can adopt to safeguard their crops.

What is Plant Biosecurity?

Plant biosecurity is the collection of policies, scientific practices, and preventive measures designed to protect crops and natural ecosystems from harmful plant pests and pathogens.

Its primary objectives are to:

- Prevent the entry of new plant diseases.
- Detect diseases at an early stage.
- Stop the spread of pathogens.
- Minimize economic and environmental losses.
- Protect biodiversity and food security.

Plant biosecurity is a shared responsibility involving governments, research institutions, agricultural extension services, quarantine authorities, seed companies, and farmers.

Why Plant Biosecurity Matters

Modern agriculture is becoming increasingly interconnected. Seeds, fruits, vegetables, flowers, and planting materials are transported across countries and continents every day. While international trade provides many benefits, it also increases the risk of introducing dangerous plant pathogens into new regions.

A single infected plant or contaminated seed lot can introduce a disease that spreads rapidly across farms. Once established, many diseases become difficult or even impossible to eradicate.

Strong biosecurity systems help to:

- Protect crop productivity.
- Maintain export markets.
- Reduce pesticide use.
- Protect farmers' incomes.
- Preserve natural ecosystems.
- Ensure long-term food security.

Major Threats to Plant Biosecurity

1. International Trade

Global trade has increased the movement of agricultural products.

Potential sources of disease introduction include:

- Imported seeds
- Nursery plants
- Fresh fruits
- Vegetables
- Cut flowers
- Wood packaging materials

Many invasive pathogens have spread through international trade.

2. Climate Change

Climate change is altering disease patterns worldwide.

Increasing temperatures can:

- Expand the geographical range of pathogens.
- Increase survival during winter.
- Accelerate pathogen reproduction.
- Create favorable conditions for disease outbreaks.

Extreme rainfall and flooding also help spread fungal and bacterial pathogens.

3. Human Movement

Travelers sometimes unknowingly carry infected fruits, seeds, or ornamental plants across borders. Even a small quantity of infected plant material can introduce dangerous diseases into new regions.

4. Natural Spread

Some pathogens spread naturally through:

- Wind
- Rain splash
- Rivers
- Insects
- Birds
- Wild plants

These natural pathways make disease management challenging once a pathogen becomes established.

Examples of Emerging Plant Diseases

Several plant diseases have become major global threats due to increased movement and environmental changes.

Banana Fusarium Wilt (Tropical Race 4)

This destructive soil-borne fungal disease affects banana plantations worldwide.

Characteristics:

- Causes plant wilting
- Blocks water transport
- Survives in soil for many years
- Difficult to eradicate

Wheat Blast

Originally reported in South America, wheat blast has spread to Asia and threatens wheat production.

Symptoms include:

- Bleached wheat spikes
- Poor grain filling
- Significant yield losses

Citrus Greening Disease

Also known as Huanglongbing (HLB), this bacterial disease has devastated citrus orchards in many countries.

Symptoms include:

- Yellow leaves
- Misshapen fruits
- Declining tree health
- Eventual tree death

Tomato Brown Rugose Fruit Virus (ToBRFV)

A recently emerging viral disease affecting tomato and pepper crops.

Symptoms include:

- Mosaic leaves
- Brown fruit patches
- Reduced market value

The virus spreads easily through contaminated tools, hands, and infected seeds.

Components of Plant Biosecurity**1. Prevention**

Prevention is the first and most effective step.

Farmers should:

- Purchase certified seeds.
- Avoid unknown planting materials.
- Inspect nursery plants before planting.
- Follow quarantine regulations.

2. Early Detection

Early detection greatly improves disease management.

Farmers should regularly inspect crops for:

- Leaf spots
- Wilting
- Yellowing
- Stem cankers

- Fruit rots
 - Unusual growth patterns
- Any unusual symptoms should be reported immediately to agricultural experts.

3. Rapid Response

Once a new disease is detected:

- Remove infected plants.
 - Destroy infected residues.
 - Restrict movement of equipment.
 - Avoid transporting infected produce.
- Rapid action prevents widespread outbreaks.

4. Surveillance

Governments and agricultural agencies continuously monitor crops for new diseases.

Surveillance includes:

- Field inspections
- Laboratory testing
- Molecular diagnostics
- Disease mapping
- Digital monitoring systems

Role of Modern Technology

Technology has transformed plant biosecurity.

Artificial Intelligence (AI)

AI systems analyze leaf images and identify diseases within seconds.

Benefits:

- Fast diagnosis
- High accuracy
- Reduced dependence on experts
- Smartphone accessibility

Remote Sensing

Satellites and drones monitor crop health over large areas.

These technologies identify disease hotspots before symptoms become severe.

Molecular Diagnostics

Modern laboratory techniques include:

- PCR
- Real-Time PCR
- DNA sequencing
- CRISPR-based diagnostics

These methods detect pathogens quickly and accurately.

Internet of Things (IoT)

Field sensors continuously monitor:

- Temperature
- Humidity
- Soil moisture

- Leaf wetness

The collected data help predict disease outbreaks.

Importance of Quarantine

Plant quarantine is one of the strongest biosecurity tools.

It involves:

- Inspection of imported plants
- Laboratory testing
- Restriction of infected materials
- Certification systems

Without quarantine, dangerous pathogens could spread rapidly between countries.

Farmer's Role in Plant Biosecurity

Farmers play the most important role because they are the first to observe unusual symptoms.

Farmers should:

- Buy certified seeds.
- Avoid illegal seed imports.
- Keep fields clean.
- Sanitize tools regularly.
- Remove infected plants immediately.
- Practice crop rotation.
- Control insect vectors.
- Report unusual diseases quickly.
- Maintain proper farm hygiene.

Farm Biosecurity Practices

Simple biosecurity measures include:

Equipment Hygiene

Clean:

- Tractors
- Harvesters
- Sprayers
- Pruning tools
- Footwear

This reduces pathogen movement between fields.

Visitor Management

Visitors should:

- Use clean footwear.
- Avoid entering infected fields.
- Follow farm hygiene rules.

Weed Management

Many weeds act as alternate hosts for plant pathogens.

Regular weed control reduces disease reservoirs.

Water Management

Use clean irrigation water.

Contaminated water may spread fungal and bacterial pathogens.

Economic Importance of Plant Biosecurity

Strong plant biosecurity benefits farmers by:

- Increasing crop yield.
- Improving produce quality.
- Reducing pesticide costs.
- Protecting export markets.
- Increasing farm profitability.
- Reducing disease outbreaks.

Countries with strong biosecurity systems experience fewer invasive plant diseases and lower economic losses.

Challenges in Plant Biosecurity

Several challenges remain:

- Climate change
- Increased global trade
- Fungicide resistance
- Limited farmer awareness
- Inadequate surveillance
- Lack of rapid diagnostics in remote areas

Continuous research and farmer education are essential to overcome these challenges.

Future of Plant Biosecurity

The future of plant biosecurity lies in integrating advanced technologies with traditional farming practices.

Emerging innovations include:

- AI-powered disease diagnosis
- Drone-based surveillance
- Portable DNA testing kits
- Smart biosensors
- Digital disease forecasting
- Climate-based disease prediction
- CRISPR-based pathogen detection
- Automated quarantine monitoring

These technologies will enable faster detection and more effective management of emerging plant diseases.

Practical Tips for Farmers

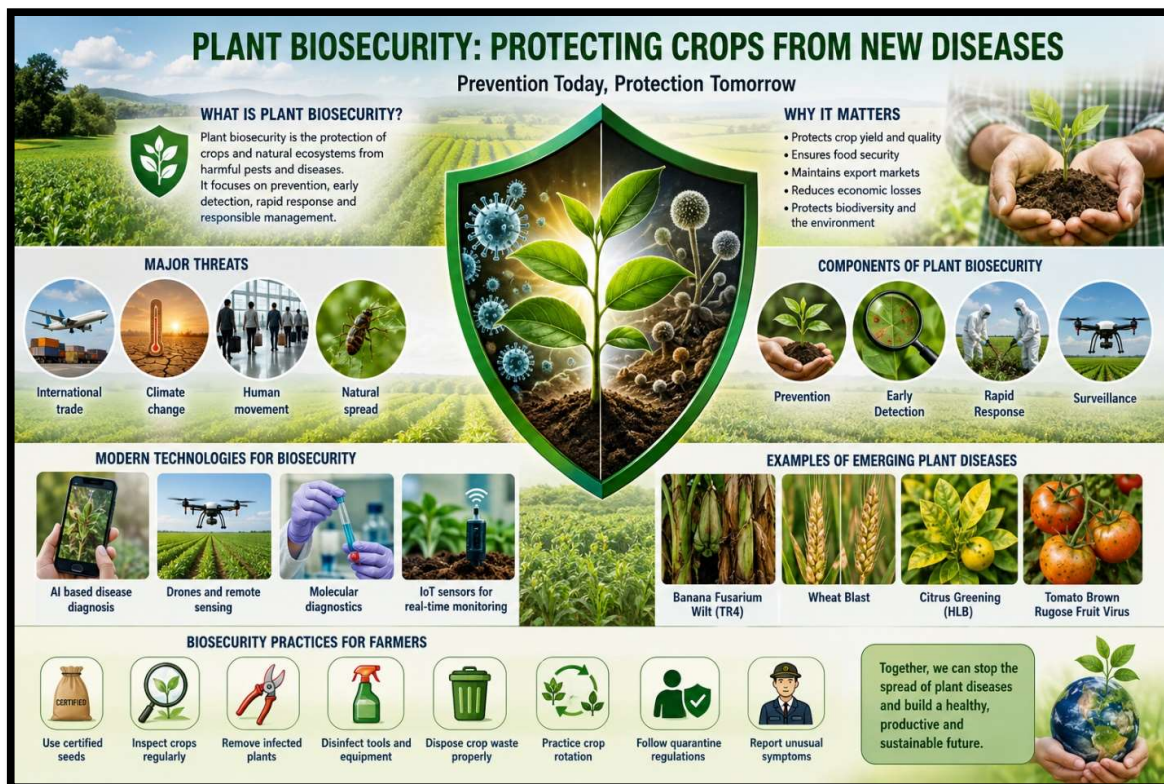
To strengthen biosecurity on the farm:

1. Always purchase certified, disease-free seeds.
2. Inspect crops every week for unusual symptoms.
3. Remove and destroy infected plants immediately.
4. Disinfect farm tools before moving between fields.
5. Avoid using unknown planting materials.
6. Practice crop rotation.
7. Maintain balanced fertilization.

8. Use resistant crop varieties whenever available.
9. Follow government quarantine regulations.
10. Seek advice from agricultural extension officers when unfamiliar diseases appear.

Conclusion

Plant biosecurity has become an essential component of modern agriculture. As global trade, climate change, and emerging pathogens continue to increase the risk of disease outbreaks, preventive strategies are more important than ever. Farmers are the first line of defense and play a vital role in protecting crops through good hygiene, careful monitoring, the use of certified planting material, and rapid reporting of suspicious symptoms. Modern technologies such as artificial intelligence, drones, molecular diagnostics, and digital surveillance are making plant biosecurity more efficient and accessible. However, technology alone is not enough. Success depends on collaboration among farmers, scientists, governments, and agricultural organizations. By adopting strong biosecurity practices, farmers can reduce crop losses, lower production costs, protect the environment, and contribute to national and global food security. In an era of increasing agricultural challenges, investing in plant biosecurity is not just a protective measure—it is a long-term strategy for sustainable farming and a resilient agricultural future.



TURKEY BERRY: THE TINY GREEN SUPERFOOD WITH POWERFUL HEALTH BENEFITS

Karakambadi Vaishnavi^{1*}, Syed Sadarunnisa² and Sangaraju Reddy Veera Nagaveni³

¹PhD Scholar, Dr. Y.S.R. Horticultural University, College of Horticulture, Anantharajupeta-516105, Andhra Pradesh, India

²Professor, Department of Vegetable Science, Dr. Y.S.R. Horticultural University, College of Horticulture, Pulivendula-516390, Andhra Pradesh, India

³PhD Scholar, Department of Vegetable Science, College of Agriculture – JNKVV

*Corresponding Email: vaishnavikarakambadi1998@gmail.com

Abstract

Solanum torvum Sw., commonly known as Turkey berry, is a nutrient-rich yet underutilized vegetable belonging to the family Solanaceae. Native to Central and South America, it is now widely naturalized across tropical Asia, Africa and the Caribbean. The plant is valued both as a traditional vegetable and as a medicinal resource in several cultures. Its fruits and leaves are rich in iron, vitamins, dietary fiber and bioactive phytochemicals such as alkaloids, flavonoids, tannins and saponins. Traditionally used to manage anaemia, hypertension, infections and digestive disorders, modern research supports its antioxidant, antimicrobial, anti-inflammatory and cardioprotective properties. Adapted to diverse agro-climatic conditions and capable of thriving under low-input systems, Turkey berry holds significant promise for nutritional security, sustainable agriculture, and functional food development. Reviving interest in this “forgotten berry” could contribute to combating hidden hunger and promoting climate-resilient food systems.

Key Words: Turkey berry, *Solanum torvum*, underutilized vegetable, nutritional security, phytochemicals

Introduction

Underutilized plant species represent an important yet overlooked resource for combating micronutrient malnutrition and improving dietary diversity in developing countries. Among them, *Solanum torvum* Sw., commonly referred to as Turkey berry, is gaining recognition for its dual nutritional and therapeutic value. A member of the family Solanaceae which is one of the largest and economically significant angiosperm families encompassing nearly 3,000 species. *S. torvum* has long been integrated into traditional food systems and ethnomedicinal practices. Though frequently seen growing wild, this hardy shrub has quietly supported rural nutrition and traditional healthcare systems for generations. Despite its widespread use in South India, Ghana, Jamaica and Southeast Asia, Turkey berry remains largely neglected in mainstream agriculture and research. However, increasing interest in functional foods and climate-resilient crops has brought renewed attention to its remarkable nutritional and pharmacological properties.

Origin and distribution

Solanum torvum is believed to have originated in the tropical regions of Central and South America, from where it gradually disseminated to other parts of the world through human migration, trade and ecological adaptation. Over time, the species has become widely naturalized

and cultivated across the tropics, including India, Ghana, the West Indies and Caribbean islands, Southeast Asia and several countries in tropical Africa. In India, it is particularly well established in the southern states such as Tamil Nadu, Andhra Pradesh, Kerala and parts of Karnataka, where it is commonly known as Sundakkai or Ustikaya or Adavi vankaya and forms an integral component of traditional cuisine. In Ghana, it is locally referred to as “Kwahu nsusua” or “Abeduru,” and holds notable dietary and cultural significance, especially in maternal nutrition and postpartum recovery practices.

Botany

Solanum torvum is an erect, robust and often spiny shrub or small tree that typically attains a height of 2-5 meters, with its growth habit varying from annual to perennial depending on environmental conditions. The stem is generally pubescent, covered with soft hairs and may bear prickles in certain ecotypes. Leaves are arranged alternately, simple in structure, and exhibit considerable morphological variation, ranging from entire to lobed forms; they are often pubescent and moderately large, contributing to the plant's vigorous canopy. The inflorescences bear white, star-shaped to bell-shaped flowers characteristic of the Solanaceae family. Fruits are borne in compact clusters and are small, globose berries that remain green when immature and turn yellow upon full ripening. These berries possess a slightly bitter and acid taste with a distinct pepper-like aroma and contain numerous flattened, round, brown seeds embedded within a thin fleshy pericarp Abraham *et al.*, (2022).

Nutritional composition: A natural micronutrient booster

Turkey berry (*Solanum torvum*) is increasingly acknowledged for its dense micronutrient profile, which underpins its longstanding reputation as a “blood-building” food in traditional diets. The proximate composition of fresh fruits of *Solanum torvum* on a percentage basis contains moisture ($79.81 \pm 0.49\%$), carbohydrate ($0.33 \pm 0.03\%$), crude fat ($8.81 \pm 1.46\%$), protein ($10.72 \pm 0.51\%$), ash ($0.06 \pm 0.004\%$) and crude fibre ($25.12 \pm 1.92\%$). Fresh fruits of *Solanum torvum* were found to contain micronutrients (mg/kg) such as copper 14.97, zinc 16.58, iron 208.43 and manganese 102.83, along with macro minerals (%) including sodium 0.31, magnesium 0.32, phosphorus 0.58, calcium 0.47, potassium 1.84 and sulphate 1.50. The vitamin spectrum of *S. torvum* encompasses vitamin A and several B-complex vitamins, notably thiamine (B₁), niacin (B₃) and pyridoxine (B₆), which collectively contribute to metabolic regulation and overall physiological well-being. Furthermore, the fruit contains dietary fiber that supports digestive health and enhances nutrient assimilation. In the context of rising micronutrient malnutrition, often described as “hidden hunger,” Turkey berry represents an accessible, culturally accepted and nutritionally strategic food resource capable of improving dietary quality in vulnerable populations Abraham *et al.*, (2022).

Medicinal uses

Solanum torvum has been extensively integrated into traditional medicinal systems across Africa and Asia, where various plant parts are employed in the management and prevention of multiple ailments. Ethnomedicinal reports indicate its use in treating anemia, arterial hypertension, fever, cough, wounds, tooth decay, reproductive disorders and inflammatory conditions. Experimental and review evidence attribute these therapeutic effects to its rich phytochemical composition, particularly alkaloids, flavonoids, tannins, saponins and glycosides, which exhibit antioxidant, anti-inflammatory, analgesic, antimicrobial, cardioprotective and antihypertensive activities. In Ghana, soups prepared from the fruits are traditionally administered to postpartum mothers to enhance recovery, improve hematological status, and stimulate lactation, reflecting its haemopoietic and

nutritive roles Ganguly *et al.* (2024). Collectively, both ethnobotanical knowledge and emerging pharmacological evidence support the broad-spectrum medicinal relevance of Turkey berry Darkwah *et al.*, (2020).

Cultivation and agronomic potential

Solanum torvum exhibits remarkable ecological adaptability, making it a resilient and low-input crop suited to tropical and subtropical production systems. The species thrives under warm climatic conditions, tolerates intermittent drought and performs satisfactorily under moderate shade, characteristics that enable its integration into mixed and agroforestry-based cropping systems. Its ability to grow in relatively poor and marginal soils, coupled with modest nutrient requirements, reduces dependence on external inputs. These traits make Turkey berry particularly valuable for smallholder farmers and home gardens, where resource constraints often limit crop choices. Furthermore, *S. torvum* is widely utilized as a rootstock for eggplant (*Solanum melongena*) due to its tolerance to certain soil-borne pathogens and nematodes, thereby enhancing graft compatibility and crop resilience. In the context of increasing climate variability and rising production costs, such hardy and multipurpose crops offer viable alternatives for sustainable and diversified farming systems.

Role in nutritional security and sustainable agriculture

The growing global emphasis on combating malnutrition and adapting agriculture to climate change has renewed interest in underutilized crops such as Turkey berry. Beyond its nutritional richness, the crop's adaptability to harsh environmental conditions enhances its relevance within climate-smart agricultural frameworks. Its multifunctional role as both food and traditional medicine strengthens its value in rural communities, where health and nutrition are closely linked to agricultural biodiversity. Incorporating Turkey berry into nutrition gardens, school feeding programs and community-based food systems could contribute meaningfully to dietary diversification, household food security, and sustainable agricultural intensification.

Future prospects

Although *Solanum torvum* has demonstrated significant nutritional and pharmacological potential, it remains insufficiently explored in structured research and crop improvement programs. Future studies should focus on standardizing and characterizing its phytochemical constituents, along with clinical validation of traditional medicinal claims to establish evidence-based applications. Breeding improved cultivars with higher yield, reduced bitterness, and enhanced nutrient content will support wider adoption. Additionally, research on post-harvest processing, value addition, and integration into nutrition-sensitive agricultural policies through interdisciplinary collaboration is essential to fully harness its potential.

Conclusion

Solanum torvum exemplifies the convergence of traditional wisdom and contemporary scientific validation. Once regarded primarily as a wild or semi-domesticated shrub, it is increasingly recognized as a functional food with significant nutritional and therapeutic potential. Its agronomic resilience, micronutrient richness and diverse bioactive compounds collectively underscore its relevance in addressing the intertwined challenges of malnutrition, climate change, and sustainable food production. Elevating the status of such underutilized crops within research, policy and extension systems is imperative for building resilient, inclusive and nutrition-oriented agricultural landscapes. Through informed promotion and scientific advancement, Turkey berry

can transition from a neglected resource to a cornerstone of sustainable and health-centered food systems.

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Fig.1. Flowering stage of Turkey berry



Fig.2.Clustered immature fruits of Turkey berry

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MANAGEMENT STRATEGIES FOR TOMATO PESTS AND DISEASES

**M. Sukumari, T. Shirisha, I. Alekhya Reddy,
Y. Sreyas Yagnik and M. Venu Gopal Reddy**

Department of Horticulture (Vegetable Science) School of Agricultural Sciences,
Malla Reddy University, Hyderabad, Telangana, 500043

Abstract

Tomato is one of the most widely cultivated vegetable crops, but its production is severely affected by numerous insect pests and diseases. Major pests such as fruit borer, whiteflies, aphids, and thrips, along with diseases like damping-off, early and late blight, bacterial wilt, and viral leaf curl, cause significant yield and quality losses. Effective pest and disease management in tomato relies on an integrated approach that combines cultural, mechanical, biological, and chemical control methods. Practices such as using certified seeds, resistant varieties, crop rotation, field sanitation, biological control agents, and need-based pesticide application help reduce infestation. Integrated Pest and Disease Management (IPDM) ensures sustainable production, minimizes environmental hazards, lowers production costs, and improves both yield and fruit quality for better market returns.

Introduction

Tomato is an important vegetable crop that is affected by many insect pests and diseases, which reduce yield and fruit quality. Major pests include fruit borer, whiteflies, aphids, and thrips, while common diseases are damping-off, blight, wilt, and viral diseases. Pest and disease management in tomato aims to control these problems through preventive and integrated methods. It includes the use of healthy seeds, resistant varieties, crop rotation, biological control, and need-based chemical application. Proper management ensures higher yield, better quality fruits, and sustainable production.

Integrated Pest and Disease Management (IPDM) in Tomato is a sustainable and eco-friendly strategy that integrates cultural, mechanical, biological, and chemical methods to control pests and diseases effectively while minimizing environmental hazards.

1. Cultural Practices

- Use certified and disease-free seeds along with resistant varieties (especially against wilt and leaf curl).
- Practice crop rotation with non-solanaceous crops; avoid growing chilli, brinjal, and potato continuously.
- Maintain recommended spacing to ensure proper air circulation.
- Remove and destroy diseased plants and infected plant parts regularly.
- Follow strict field sanitation and deep summer ploughing to expose soil-borne pests.
- Apply balanced fertilizers and avoid excessive nitrogen application

Importance of Trap Crop in Tomato

- Attracts pests away from tomato plants.
- Reduces insect damage and pest infestation.

- Decreases pesticide use.
- Eco-friendly method of pest control.

Importance of Pheromone Traps in Tomato

- Used to attract and trap insect pests, especially fruit borers.
- Helps in early detection and monitoring of pests.
- Reduces pest population in tomato fields.
- Minimizes use of chemical pesticides.
- Eco-friendly and safe method of pest control.
- Improves yield and quality of tomato fruits.

2. Seed Treatment

Treat seeds with *Trichoderma viride* @ 4 g/kg of seed to protect against soil-borne pathogens.

- Alternatively, treat seeds with Carbendazim or Thiram @ 2 g/kg of seed to prevent damping-off and other seed-borne diseases.

3. Mechanical and Physical Methods

- Install yellow sticky traps to monitor and control whiteflies and aphids.
- Use blue sticky traps for thrips management.
- Handpick and destroy fruit borer larvae and damaged fruits.

4. Biological Control

- Release *Trichogramma chilonis* @ 50,000 per acre against fruit borer.
- Spray *Bacillus thuringiensis* (Bt) formulations to control caterpillars.
- Conserve natural enemies such as ladybird beetles and spiders.
- Apply neem-based products like NSKE 5% or neem oil 2% as botanical pesticides.

5. Chemical Control (Need-Based Application)

- For fruit borer: spray Emamectin benzoate or Spinosad.
- For whiteflies (vector of leaf curl virus): use Imidacloprid or Thiamethoxam. For early and late blight: spray Mancozeb or Metalaxyl + Mancozeb.
- Apply chemicals only at recommended doses and observe proper waiting periods

6. Major Diseases Managed

- Damping-off
- Early blight
- Late blight
- Bacterial wilt
- Tomato leaf curl virus

Conclusion

Proper pest and disease management is crucial for obtaining high yield and superior quality tomato fruits. As tomato crops are prone to many insect pests and diseases, an integrated management approach is essential. Integrated Pest and Disease Management (IPDM) utilizes a combination of cultural, mechanical, biological, and chemical methods to manage pests effectively in an economical and environmentally safe way.

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THE ORGANIC AWAKENING: FROM NICHE HABIT TO EVERYDAY CHOICE

Adhi Sri Latha

Teaching Associate, Department of Resource Management and Consumer Sciences,
CCSc., PJTAU, Hyderabad- 500004

Corresponding Email: adisrilatha20@gmail.com

From Fringe to Fridge: How Consumer Perception of Organic Food Has Changed

Not long ago, "organic" was a label you would find tucked into a corner of the grocery store, favoured mostly by a small, health-obsessed crowd willing to pay extra for a slightly bruised apple. Today, organic aisles have expanded, mainstream supermarket chains stock private-label organic lines and the word itself have become a mainstream purchase cue rather than a niche identity marker. The story of how that happened is really a story about how people think — about health, trust, money and what they're willing to put in their bodies.

The Numbers Tell the Story

India's organic story is moving even faster. The India organic food market was valued at approximately USD 2.3 billion in 2025 and is projected to reach USD 11.3 billion by 2034, growing at a compound annual growth rate of roughly 19–22% — nearly three times the pace of the mature U.S. market. That growth is being fuelled by rising urban health consciousness, expanding organized retail and e-commerce and government-backed programs like the National Programme for Organic Production (NPOP) and Paramparagat Krishi Vikas Yojana (PKVY).

India also holds a unique position globally: it's home to the largest number of organic producers in the world and supplies 40–50% of the world's organic spice imports. Domestic consumption is catching up to exports too — it now accounts for over half of total organic food value in India, a reversal from a decade ago when exports dominated. Still, organic farming covers only 3–5% of India's total agricultural land, meaning the market's runway for growth remains long.

From "Chemical-Free" to "Functional Food"

The earliest wave of organic buyers cared mostly about absence: no synthetic pesticides, no GMOs, no artificial anything. That's still part of the appeal, but it's no longer the whole pitch. Consumers have shifted from thinking about food purely in terms of avoiding harmful ingredients to actively seeking products that deliver tangible health benefits — a shift from "food as fuel" to "food as medicine. Organic brands have had to respond by justifying their premium prices with nutrition, not just purity — foregrounding protein, fibre and functional ingredients rather than simply what's missing from the label. This marks a genuine change in mindset: organic isn't just the "safe" choice anymore, it's expected to actively do something for the people buying it.

Trust Has Replaced Blind Faith

Perhaps the biggest shift is in consumer sophistication. Shoppers are no longer taking the word "organic" at face value — they're reading labels, questioning certifications and demanding proof. Surveys show that while transparency has become one of the most important purchase factors, many consumers still don't fully understand what organic certification actually guarantees — often valuing claims like "no added hormones" or "raised without antibiotics" more highly than the organic label itself, even though certified organic already covers those bases.

That gap between trust and understanding has pushed brands to get specific. Vague sustainability talk doesn't cut it anymore; shoppers want named certifications, measurable acreage and concrete claims they can verify. In parallel, a newer signal is gaining ground fast: how processed a food is now matters more to many shoppers than whether it's organic, non-GMO or "regenerative" — with roughly three-quarters of U.S. consumers actively trying to avoid ultra-processed foods. Organic, in other words, is being folded into a bigger, more demanding conversation about what "clean" really means.

Generational Divides Are Reshaping the Market

Perception of organic food isn't uniform — it splits sharply along generational lines. Among 18–29-year-olds, 61% believe organic produce is genuinely better for health, compared to just 45 % of adults 65 and older, with the gap narrowing steadily across the age groups in between. Younger consumers, particularly Gen Z, have grown up with sustainability and clean-label messaging as background noise, so trusting — and paying for — organic feels less like a leap of faith and more like a default assumption. Gen Z is leading the charge in seeking out nutrient-dense food at 41%, ahead of Millennials at 36%, Baby Boomers at 30% and Gen X at 29%.

This generational tilt matters for the industry's future: as younger, more label-literate shoppers age into their peak spending years, the market's baseline expectations around transparency and functional benefit are likely to keep climbing.

Price Is Still the Great Filter

None of this idealism erases economics. The single biggest barrier standing between organic intention and organic purchase remains price. Consumers often intend to buy organic after learning about pesticide risks, but if the price feels prohibitive or the product is hard to find, that intention doesn't always convert into an actual purchase. Rising costs of living have made the decision more deliberate almost everywhere. According to recent produce industry research, 59% of consumers say they prefer to buy healthy options when the price feels right, while only 34% are willing to pay up to a 10% premium for organic.

In response, brands have started meeting shoppers halfway — offering value-tier organic lines, in-store promotions and clearer messaging about why the premium is worth paying, rather than simply expecting loyalty to cover the gap.

Values Beyond the Plate

Health is still the leading motivator, but it's no longer the only one. For many shoppers, buying organic has become a small but tangible way to express identity: a vote for soil health, animal welfare and a food system that feels less industrial, even if they can't articulate the science behind every certification on the package.

The Bottom Line

The story of organic food's changing perception is really a story about consumers growing up. What began as a fringe, faith-based purchase — buy organic, trust it's better, pay the premium without asking too many questions — has matured into a far more demanding, evidence-hungry relationship. Today's shoppers want proof, not just promises; function, not just absence; and value, not just virtue-signalling. Organic food has won a permanent place in the mainstream cart, but it earned that place the hard way: by being scrutinized, questioned and ultimately re-justified for a generation of consumers who read the fine print before they read the price tag.

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NATURAL FARMING: THE SCIENCE BEHIND SUSTAINABLE AGRICULTURE

Jayendra Kumar, Nazia Manzar and Abhijeet Shankar Kashyap*

ICAR-National Bureau of Agriculturally Important Microorganisms, Mau,
Uttar Pradesh 275103

*Corresponding Email: abhijeet4497@gmail.com

Concept of Natural farming

Natural Farming is agro ecology, chemical free system that blends Indian tradition with modern ecology. It integrates crops, trees, and livestock to optimize functional biodiversity and on farm resources. The core practice relies on biomass mulching, soil aeration, and cow dung- urine formulation, completely excluding synthetic inputs. By maximizing resources recycling, it reduces dependency on purchased inputs, offering a cost effective approach that boosts rural employment and sustainable development.

The system is based on four fundamental principles minimizing external input, recycling farm biomass, maintaining continuous soils cover through mulching, and enhancing biological activity in the soil. Indigenous cow based formulation such as Jeevamrit, Beejamrit, and Ghan Jeevamrit, along with mulching practices, stimulate beneficial microbial population, improve nutrient cycling, and enhance soil structure. These practices not only restore soil health but also increase water use efficiency and strengthen the resilience of farming system against climate variability. (Government of India, 2025).

In recent years, Natural farming has emerged as a sustainable alternative to input intensive agriculture in India. Excessive use of chemical fertilizers and pesticides has led to decline soil health, environment pollution, rising cultivation costs, and food safety concerns. By promoting the external inputs, Natural farming enhances soil health, reduces production cost, conserves natural resources, and contributes to sustainable agriculture and climate resilience. (ICAR, 2024)

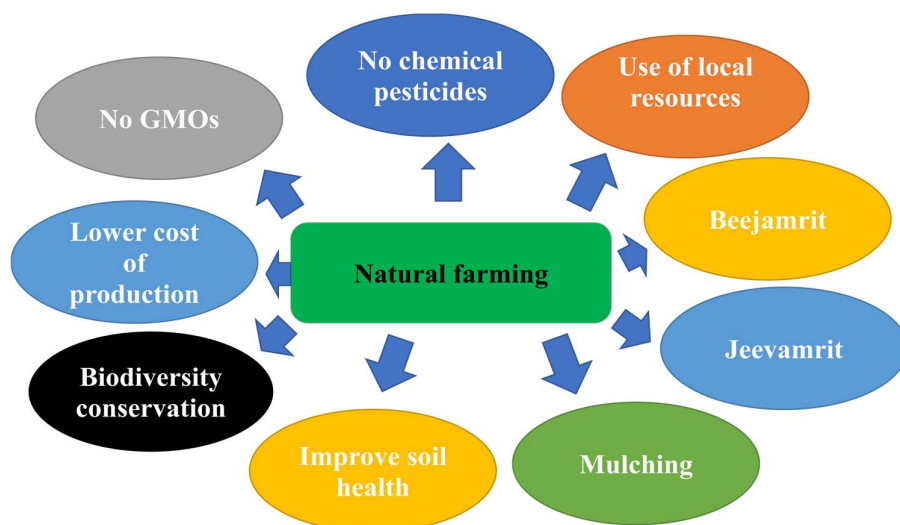


Fig. 1. Role of Natural farming for achieving sustainability in agriculture

The need for a New Farming Revaluation

Modern agriculture has improved food production but excessive dependence on chemical fertilizer and pesticides has results in declining soil fertility, loss of beneficial microorganisms, environment degradation, rising input cost, and concerns about food safety. Therefore, there is an urgent need for a sustainable farming approach that balances productivity, soil health, and farmer prosperity. Natural farming provides a pathway for new agriculture revolution by reducing external input, utilizing biological resources, and promoting natural ecological processes. The use of beneficial microorganisms, organic input, and soil friendly practices helps restore soil health, enhance nutrient cycling, and support safe food production. Integrating traditional knowledge with modern science can develop climate- resilient and economically viable farming systems for the future. (FAO. 2017).

What exactly is Natural Farming

Natural farming is an ecological and science- based farming system that promote crop production by utilizing natural process and reducing dependence on synthetic fertilizers and pesticides. It focuses on improving soil health, enhancing biodiversity, and using locally available resource to develop a sustainable agriculture ecosystem. In natural farming, soil is considered a living system where microorganisms, organic matter, and plant interact to improve nutrient cycling, plant growth, and soil fertility. The use of beneficial microorganisms, organic input biochar, and compost- based preparation, and biological pest management healthy soil and safe food production. Natural farming combined traditional agriculture knowledge with modern scientific approaches to achieve sustainable productivity; climate resilience reduced input cost, and improved farmer livelihoods. (Government of India. 2024).

The Hidden Life beneath our Feet

Soil is a living ecosystem that contains a diversity of microorganisms, including bacteria and fungi, essential roles in maintaining health and plant productivity. These hidden microbial communities regulate nutrient cycling, organic matter decomposition, plant growth promotion and suppression of soil borne diseases. Beneficial microorganisms improve nutrient availability, enhance root development, and increase plant resilience against environment stresses. Maintaining microbial diversity is therefore for sustainable agriculture and long term soil fertility. In natural farming these natural microbes processes through biological inputs and eco- friendly practices helps restore soil health and supports sustainable crops production. (Van *et al.* 2008).

The science behind Natural farming

Natural farming is based on the scientific understanding that soil, plant and microorganism function together as a balanced ecosystem. Soil microorganisms play a key role in nutrient cycling, organic matter decomposition, plant growth promotion and disease suppression. Microbial input, compost- based preparation biological pest management enhances soil health, improve nutrient efficiency and support sustainable crop production. Natural farming combines ecological principles with modern soil microbiology to promote healthy soils, safe food and resilient agriculture.

Natural farming and Climate change

Climate change poses significant challenges to agriculture through rising temperatures, irregular rainfall, soil degradation, and increased crop stress. Natural farming help address these challenges by improving soil health, enhancing biological activity, and increasing ecosystem resilience. Practice such as organic inputs, microbial- based formulation mulching and reduced chemical use

improve soil organic carbon water retention and nutrient cycling. Healthy soils can store more carbon and support better crops performance under climate stress. (Lal 2020).

The Future of Natural farming

The future of agriculture depends on developing farming systems that ensure food security while protecting soil health and natural resources. Excessive use of chemical inputs has created challenge such as soil degradation, loss of biodiversity and increasing production casts. Natural farming provides a sustainable pathway by working with ecological processes and reducing dependence on external inputs. Enhancing soil microbial activity, improving nutrient cycling, conserving water and promoting biodiversity. Natural farming supports resilient and sustainable crops production. The integration of traditional knowledge with modern science. Microbial technology and biological inputs further enhance its effectiveness. Natural farming represents a toward healthy soils, safe food production, climate resilient agriculture and prosperous farming communities for the future of sustainable agriculture.

Conclusion

Natural farming represents a scientific and sustainable approach to agriculture that work in harmony with nature rather than relying on synthetic inputs. Improving soil health, enhancing microbial diversity promoting efficient nutrient cycling and conserving natural resource and environmentally friendly farming systems. The integration of traditional knowledge with modern scientific insights offers new opportunities to address the critical challenge of soil degradation, climate change, food safety and rising cultivation cast. Research and field experience continue to expand, natural farming has the potential to become a cornerstone of sustainable agriculture. With continued validation, policy support and active farmer participation it can significantly contribute to sustaining healthy soil. Ultimately future of agriculture depends not only on enhancing food production but also on doing so in ways that protect the environment and ensure well-being of future generation.

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INTEGRATING MICROBIOME DYNAMICS INTO PREDICTIVE MODELS FOR PLANT DISEASES

Laikangbam Raymond Singh¹, Sumiah Wani², Diksha Banal¹,
Dasari Meghnath², Parveez Ahmad Sheikh¹ and Aflaq Hamid²

¹Division of Plant Pathology, Faculty of Agriculture, Sheri-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

²DNA fingerprinting and advanced plant virology laboratory, AICRP-NSP, Sheri-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

*Corresponding Email: stalwartmegham@gmail.com

Abstract

Plant diseases cause major agricultural losses worldwide, affecting yield and quality. Early and accurate prediction systems are required for disease management. The conventional model relies on environmental parameters often unreliable and fail to explain variability in disease outcomes. Recent advances highlight that microbiome dynamics shifts in rhizosphere, phyllosphere and endosphere can predict disease earlier. Integrating temporal and spatial microbiomic data with multi-omics approaches, including amplicon sequencing, metagenomics, meta-transcriptomics and metabolomics, enhances the accuracy. Statistical and machine learning tools further enable the identification of key microbial indicators. Despite challenges in standardization and implementation, microbiome-informed predictive models offer a promising framework for sustainable and precise, and effective plant disease management.

Keywords: Plant microbiome, disease prediction, microbiome dynamics, statistical analysis.

Introduction

Diseases constitute one of the major constraints to agriculture; when combined with pest damage, they are responsible for up to 40% of global crop losses annually (FAO, 2025). So, forecasting and early detection of disease are essential for preventive measures that can be applied well in advance (Martinelli *et al.*, 2015; Charaya *et al.*, 2021). In conventional plant disease prediction models, the focus is primarily on identifying environmental conditions conducive to pathogen infection, disease development, and pathogen spread (Agrios, 2005). For example, to predict potato diseases, historically used temperature and humidity thresholds to identify periods of high infection risk (Austin Bourke 1964; Savary *et al.* 2017). They are unable to explain the substantial variation in disease outcomes that is observed under uniform conditions. In recent findings, small changes in rhizosphere microbiome composition can predict disease outcomes earlier and more accurately than pathogen density variations (Gu *et al.*, 2022). Temporal and spatial shifts in community composition during plant development and disease-induced changes in microbial communities all influence disease progression but are not represented in traditional prediction frameworks. These limitations of traditional disease prediction approaches have motivated the development of microbiome-integrated prediction models.

Microbiome Model for Disease Prediction

Microbiome refers to the microbial community with its surrounding habitat. It includes all the microbial activity and its interaction with the environment (Copeland *et al.*, 2025). Plant

microbiomes present in the rhizosphere, phyllosphere and endosphere play important role in plant growth and its function (Vorholt *et al.*, 2012; Lemanceau *et al.*, 2017). They are dynamic in nature, referring to the temporal and spatial changes in microbial community composition, structure, diversity and functional activities that occur in response to biotic and abiotic factors (Edwards *et al.*, 2018; Weit *et al.*, 2019). By combining both temporal and spatial microbiome data, it is possible to develop a predictive model that predicts the disease early and enhances, ultimately promoting sustainable agricultural practices.

Developing prediction models begins with sampling strategies to capture microbiome dynamics for both spatial and temporal variability. For capturing the temporal dynamics, sampling is conducted across multiple timepoints, including the plant developmental stages, environmental changes and disease progression. It enables the detection of early microbiome shifts before visible disease symptoms appear in the plants (Gu *et al.*, 2022). Therefore, an appropriate spatial and temporal sampling design is essential for generating reliable microbiome data. The collected samples are then analysed using different omics approaches to study microbial composition and function. The data collected provides information about the micro-ecology and helps investigate the interactions between microorganisms and their surroundings. The choice of data types depends on available resources and the specific disease system. Amplicon sequencing is widely used in disease prediction studies, where bacterial communities are profiled using 16S rRNA gene sequencing, while fungal communities are characterized through ITS (internal transcribed spacer) sequencing. Studies have successfully used 16S rRNA amplicon data to predict huanglongbing (HLB) occurrence in citrus with near-perfect accuracy, identifying 28 bacterial genera in the rhizosphere and 17 bacterial species in the phyllosphere as predictive biomarkers (Liu *et al.*, 2023). Metagenomic sequencing provides information on the functional genetic potential of microbiomes, revealing the presence and abundance of functional genes (Chouhan *et al.*, 2023). It has been used for multiclass disease classification, achieving over 70% accuracy in discriminating between 18 different disease states and healthy conditions (Khan & Kelly, 2019; Karwowska *et al.*, 2025). Unlike DNA-based approaches that measure potential functions, meta-transcriptomics reveals which genes are actually being expressed and at what levels, providing direct microbial activity (Douglas *et al.*, 2020; Segata *et al.*, 2011). Small molecule metabolites produced by microbiomes and plants, including the antimicrobial compounds, signalling molecules, nutrients, and plant defence compounds, are characterized by metabolomic profiling (Zhou *et al.*, 2025). It gives information about the chemical interaction between the plants, microbes and pathogens that determine the disease outcomes. Integration of metabolomic data with microbiome profiles enhances predictive accuracy and mechanistic understanding of disease processes (Fournier *et al.*, 2025). The generated data are further analysed using statistical and computational methods.

The data collected are then subjected to statistical methods to quantify differences and identify the patterns associated with plant health and disease. Analysis of variance and t-test come under univariate statistical tests, which are used to compare the alpha diversity or individual taxon abundance between the healthy and diseased plants. These methods test whether helps to identify the specific microbial features that differ significantly between treatment groups or disease states (Yuan *et al.*, 2020). Permutational multivariate analysis of variance (PERMANOVA) tests whether microbial community composition differs significantly between groups based on distance or dissimilarity matrices. This non-parametric approach makes fewer distributional assumptions than parametric multivariate methods, making it well-suited for microbiome data.

A range of statistical approaches is applied to interpret the univariate or multivariate data and extract biologically meaningful patterns related to plant disease. These methods help to identify the pattern associated with plant health disease. Principal component analysis (PCA) and principal coordinates analysis (PCoA, also called metric multidimensional scaling) are linear ordination methods that identify major axes of variation in community composition. PCoA based on Bray-Curtis or UniFrac distances is particularly common in microbiome studies, revealing clustering patterns associated with disease status, plant compartment, or environmental gradients (Liu *et al.*, 2023; Yuan *et al.*, 2020).

The goal of microbial-based disease prediction is to identify the specific microbial taxa that differ in abundance between the healthy and diseased plants. Linear discriminant analysis effect size (LEfSe) combines statistical significance testing with biological relevance assessment, identifies the taxa that are statistically different and have large effect sizes (Yuan *et al.*, 2020; Gu *et al.*, 2022). DESeq2, originally developed for RNA-seq differential expression analysis, has been adapted for microbiome differential abundance testing. This method models count data using negative binomial distributions and includes normalization procedures that account for varying sequencing depths and compositional effects (Stopnisek and Shade, 2020). The identified microbial features are then used for disease prediction modelling.

Linear regression models predict continuous disease severity or pathogen abundance in the microbiome, while logistic regression predicts disease presence/absence outcomes. Logistic regression has been applied to predict Fusarium wilt occurrence, achieving high accuracy by integrating microbial community composition with environmental variables (Yuan *et al.*, 2020). Machine learning, such as random forest, support vector machines, neural networks and gradient boosting, is widely used in microbiome-based disease prediction (Zhao *et al.*, 2023). Random forest models achieved nearly 100 % accuracy for HLB prediction in citrus using bacterial community data from rhizosphere and phyllosphere compartments (Liu *et al.*, 2023).

Application

Research shows that rhizosphere microbiome composition can predict disease outcomes significantly earlier than traditional pathogen monitoring. In tomato bacterial wilt, small microbiome shifts predicted disease outcomes two weeks before pathogen density differences appeared between healthy and diseased plant groups (Gu *et al.*, 2022). Integrating microbiome data into spatial risk mapping frameworks enables precise identification of disease-prone areas and supports targeted intervention strategies. Predictive microbial functional profiling enables forecasting of specific diseases based on soil microbiome composition and functional potential. Specific microbial taxa are also indicators of soil health and crop productivity. In areca nut, key taxa including *Pyrinomonadaceae*, *Nitrososphaeraceae*, and *Candidatus udaeobacter* were identified as significant indicators for predicting crop yields, helping farmers to improve crop planning and resource allocation (Ganaraj *et al.*, 2025).

Conclusion

Integrating microbiome dynamics into the predictive models for plant disease management approaches is a powerful framework for understanding plant diseases and forecasting. The temporal and spatial microbiome shifts provide a sensitive early warning of disease risks. Multi-omics techniques approaches amplicon sequencing, metagenomics, meta-transcriptomics and metabolomics, when incorporated with environmental, soil, and weather data, improve disease

risk assessment. Statistical and machine learning are used for extracting predictive patterns from high-dimensional microbiome datasets. Despite the advancement, there are challenges, such as standardization of the collected data, computational complexity, cost and translation to the end-user. It also requires collaboration among the microbiologists, plant pathologists, data scientists, agronomists, and farmers, alongside technological innovation and policy support. Therefore, the application of this model may play a key role in the future in the field of sustainable agriculture.

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**DAMAGE-ASSOCIATED MOLECULAR PATTERNS: EMERGING
PLANT VACCINES FOR SUSTAINABLE DISEASE MANAGEMENT****Soumyakala M¹, Saira Banoo¹, Sumiah Wani²,
Aflaq Hamid² and Dasari Meghnath^{2*}**

¹Division of Plant Pathology, Faculty of Agriculture,
Sheri-e-Kashmir University of Agricultural Sciences and Technology of Kashmir,
Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

²DNA fingerprinting and advanced plant virology laboratory, AICRP-NSP,
Sheri-e-Kashmir University of Agricultural Sciences and Technology of Kashmir,
Shalimar Campus, Srinagar, Jammu and Kashmir -190025.

*Corresponding Email: stalwartmegham@gmail.com

Abstract

Plant diseases caused by fungi, bacteria, viruses, and oomycetes remain one of the major constraints affecting global agricultural productivity. Continuous dependence on chemical pesticides for disease management has resulted in environmental pollution, development of resistant pathogen populations, and increased concerns regarding food safety. Consequently, sustainable and eco-friendly alternatives for crop protection are urgently needed. In recent years, Damage-Associated Molecular Patterns (DAMPs) have emerged as important endogenous signaling molecules involved in plant innate immunity. DAMPs are released from damaged plant tissues during pathogen infection, herbivore attack, or abiotic stress and function as danger signals that activate defense responses. Recognition of DAMPs by pattern recognition receptors initiates signaling cascades involving calcium influx, reactive oxygen species production, mitogen-activated protein kinase activation, and phytohormone signaling pathways. Several DAMP molecules including oligogalacturonides, extracellular ATP, plant elicitor peptides, and extracellular nucleic acids have shown considerable potential in inducing broad-spectrum resistance against plant pathogens. Recent studies suggest that DAMPs may function as “plant vaccines” by priming plants for enhanced immune responses against future infections. Compared with conventional pesticides, DAMP-based approaches are environmentally safe, biodegradable, and less likely to induce resistance in pathogens. This review summarizes the major classes of plant DAMPs, their mechanisms of action, role in plant-pathogen interactions, and future prospects in sustainable disease management.

Keywords: DAMPs, plant immunity, elicitors, plant vaccines, induced resistance, sustainable agriculture

Introduction

Plants are continuously exposed to diverse pathogenic microorganisms including fungi, bacteria, viruses, nematodes, and oomycetes that significantly reduce crop productivity worldwide. Unlike animals, plants lack adaptive immune systems and therefore depend mainly on innate immunity to recognize and defend against invading pathogens. Plant innate immunity involves sophisticated defense mechanisms capable of detecting danger signals and activating appropriate immune responses (Boller and Felix, 2009).

The first layer of plant immunity is generally activated through recognition of pathogen-associated molecular patterns (PAMPs) or microbe-associated molecular patterns (MAMPs), which include

conserved microbial molecules such as chitin, flagellin, and lipopolysaccharides. These molecules are recognized by pattern recognition receptors (PRRs) located on the plant plasma membrane, resulting in activation of PAMP-triggered immunity (PTI). PTI responses include reactive oxygen species (ROS) burst, callose deposition, activation of mitogen-activated protein kinase (MAPK) cascades, and induction of defense-related genes (Bigeard *et al.*, 2015). In addition to pathogen-derived molecules, plants also recognize endogenous danger molecules released from damaged tissues. These molecules are collectively known as Damage-Associated Molecular Patterns (DAMPs). DAMPs are generated during pathogen infection, mechanical injury, herbivore attack, or abiotic stress conditions and function as alarm signals that activate immune responses in neighbouring cells and distant tissues (Hou *et al.*, 2019). Cell wall fragments, extracellular ATP, peptides, amino acids, extracellular DNA, and RNA molecules are among the important classes of plant DAMPs. Recognition of DAMPs by specific receptors activates signaling pathways similar to those involved in PTI. These pathways involve calcium influx, ROS accumulation, MAPK activation, and phytohormone-mediated defense signaling through salicylic acid, jasmonic acid, and ethylene pathways. Activation of these responses enhances resistance against a broad range of pathogens (De Lorenzo *et al.*, 2018). Recent findings have demonstrated that pattern recognition receptors act as critical guardians against pathogenic threats by integrating both PAMP- and DAMP-mediated immune signaling pathways (Zhang *et al.*, 2024).

Recent advances in molecular plant pathology have highlighted the potential application of DAMPs as “plant vaccines.” Exogenous application of DAMP molecules can prime plants for faster and stronger immune responses during subsequent pathogen attacks. Unlike conventional pesticides, DAMP-based approaches are environmentally friendly and biodegradable, making them promising alternatives for sustainable disease management. Recent investigations into pattern-triggered immunity and endogenous defense elicitors have further strengthened the possibility of utilizing DAMPs as sustainable crop protection agents in modern agriculture (Hudson *et al.*, 2024; Jones *et al.*, 2024). This review discusses the major classes of plant DAMPs, their mechanisms of perception and signaling, and their potential applications in crop protection and sustainable agriculture.

Major Classes of Plant DAMPs

Oligogalacturonides

Oligogalacturonides (OGs) are among the most extensively studied DAMPs in plants. They are fragments of homogalacturonan released from the plant cell wall during pathogen-induced degradation or mechanical injury. OGs are recognized by wall-associated kinases and activate strong defense responses including ROS production, calcium signaling, callose deposition, and activation of defense-related genes (Ferrari *et al.*, 2013). Several studies have demonstrated that OGs induce resistance against fungal pathogens such as *Botrytis cinerea*, *Fusarium oxysporum*, and *Alternaria* species. In addition to disease resistance, OGs also influence plant growth and developmental processes, indicating their multifunctional role in plant physiology.

Extracellular ATP

ATP normally functions as an intracellular energy molecule; however, cellular damage results in ATP release into the extracellular environment where it acts as a danger signal. Extracellular ATP (eATP) is recognized by receptor kinases such as DORN1, leading to activation of calcium influx, ROS generation, and transcriptional activation of defense genes (Choi *et al.*, 2014). Extracellular ATP-mediated signaling contributes to wound responses and enhances resistance against bacterial

and fungal pathogens. Recent studies indicate that eATP also plays a role in systemic signaling and immune amplification during pathogen attack.

Plant Elicitor Peptides

Plant elicitor peptides (Peps) are endogenous signaling peptides produced during tissue damage and stress conditions. These peptides are recognized by PEPR receptors and activate jasmonic acid- and ethylene-mediated defense responses. Pep signaling enhances immune priming and systemic acquired resistance in plants (Yamaguchi and Huffaker, 2011). Recent studies have highlighted the expanding role of peptide-mediated signaling in regulating plant immune responses and improving disease resistance under field conditions (Liu *et al.*, 2025; Del Corpo *et al.*, 2024). Peptide-mediated signaling has been associated with increased resistance against necrotrophic pathogens and herbivorous insects. The ability of Peps to amplify immune responses makes them attractive candidates for crop protection strategies.

Extracellular DNA and RNA

Extracellular DNA (eDNA) and RNA fragments released from damaged cells have recently been recognized as novel DAMP molecules. These nucleic acids can activate immune responses and contribute to self-recognition mechanisms in plants. Although the exact receptors and signaling mechanisms are still under investigation, studies suggest that extracellular nucleic acids induce ROS production, defense gene activation, and enhanced pathogen resistance.

Mechanisms of DAMP-Triggered Immunity

DAMP-triggered immunity begins with the recognition of endogenous danger molecules by pattern recognition receptors located on the plant plasma membrane. Binding of DAMPs to their receptors initiates rapid signaling events including ion fluxes, calcium influx, membrane depolarization, and Reactive oxygen species (ROS) production. ROS play an important role both as antimicrobial compounds and signaling molecules that regulate downstream defense pathways. ROS accumulation is followed by activation of mitogen-activated protein kinase cascades, which regulate transcriptional reprogramming and expression of defense-related genes (Bigéard *et al.*, 2015). Phytohormones including salicylic acid, jasmonic acid, and ethylene coordinate local and systemic immune responses. Salicylic acid-mediated signaling is primarily associated with resistance against biotrophic pathogens, whereas jasmonic acid and ethylene pathways are involved in defense against necrotrophic pathogens and herbivorous insects.

Activation of DAMP-triggered immunity also leads to strengthening of plant cell walls through callose deposition and lignification. In addition, plants synthesize antimicrobial metabolites and pathogenesis-related proteins that inhibit pathogen growth and spread. Recent studies indicate that DAMP signaling not only contributes to local defense responses but also induces immune priming and systemic acquired resistance, enabling plants to respond more rapidly to subsequent pathogen attacks.

DAMPs as Future Plant Vaccines

The concept of plant vaccination involves stimulation of plant immune systems prior to pathogen infection to enhance disease resistance. DAMPs have gained significant attention as potential plant vaccines because they activate broad-spectrum defense responses without directly targeting pathogens. Exogenous application of DAMP molecules can prime plants for enhanced immune responses during future pathogen attacks. This immune priming phenomenon allows plants to respond faster and more effectively to infections while minimizing energy costs associated with constitutive defense activation.

Several experimental studies have demonstrated the successful use of DAMPs in disease management. Oligogalacturonides have shown protective effects against fungal pathogens in grapevine and tomato, while peptide elicitors and extracellular ATP have enhanced resistance against bacterial pathogens in *Arabidopsis* and rice. Table 1. Compared with conventional pesticides, DAMP-based approaches offer several advantages, including biodegradability, environmental safety, reduced chemical residues, and lower risk of pathogen resistance development. DAMPs can be applied through foliar sprays, seed treatments, root applications, and nano-formulations designed for controlled release. Integration of DAMP-based technologies with nanotechnology and precision agriculture may further improve disease management efficiency in future agricultural systems.

Challenges and Future Perspectives

Despite their promising potential, several challenges currently limit the commercial application of DAMP-based technologies. One major limitation is the instability of DAMP molecules under field conditions due to degradation by environmental factors such as temperature, ultraviolet radiation, and microbial activity. Large-scale production and formulation of DAMP molecules also remain economically challenging. Furthermore, excessive activation of immune responses may negatively affect plant growth because defense mechanisms require considerable metabolic energy. Variability in DAMP responsiveness among plant species and cultivars represents another important challenge. Therefore, additional studies are required to identify highly effective DAMP molecules and optimize their delivery systems for agricultural applications.

Advances in genomics, transcriptomics, gene editing, and nanotechnology are expected to accelerate the development of DAMP-based crop protection strategies. Future research should focus on identifying novel DAMP receptors, improving formulation stability, and conducting large-scale field validation studies. Emerging evidence also suggests that epigenetic modifications such as DNA demethylation may influence DAMP-triggered immunity and immune memory in plants, opening new opportunities for sustainable crop protection strategies (Li *et al.*, 2026).

Conclusion

Damage-associated molecular patterns represent an important component of plant innate immunity and function as endogenous danger signals released during tissue damage and pathogen attack. Recognition of DAMPs activates complex defense signaling pathways that enhance resistance against diverse plant pathogens. Recent advances in plant immunology indicate that DAMPs possess considerable potential as future plant vaccines capable of inducing broad-spectrum and sustainable disease resistance. Compared with conventional pesticides, DAMP-based approaches provide environmentally safe alternatives for crop protection and may contribute significantly to sustainable agriculture. Although several challenges related to stability, formulation, and field application remain, continued research in molecular biology and biotechnology is expected to facilitate the development of effective DAMP-based disease management strategies in the near future.

Table 1. Major Plant DAMPs and their Immune Responses Against Plant Pathogens

DAMP Molecule	Molecule Class	Target Plant Species	Major Immune Responses	References
Extracellular ATP (eATP)	Nucleotides	<i>Arabidopsis thaliana</i> ,	Calcium influx, ROS production,	Chivasa <i>et al.</i> (2009); Tanaka

DAMP Molecule	Molecule Class	Target Plant Species	Major Immune Responses	References
		<i>Medicago truncatula</i> , <i>Nicotiana tabacum</i>	salicylic acid signaling, enhanced resistance against bacterial and viral pathogens	<i>et al.</i> (2014)
Extracellular NAD(P)	Nucleotides	<i>Arabidopsis thaliana</i>	Activation of PR genes, salicylic acid accumulation, disease resistance	Zhang and Mou (2009)
Extracellular DNA (eDNA)	Nucleic acids	<i>Phaseolus vulgaris</i> , <i>Zea mays</i>	Membrane depolarization, ROS burst, MAPK activation, enhanced pathogen resistance	Barbero <i>et al.</i> (2016); Duran-Flores and Heil (2017)
Systemin	Peptides	<i>Solanum lycopersicum</i>	Jasmonic acid signaling and proteinase inhibitor induction	Doares <i>et al.</i> (1995a); Ferrari <i>et al.</i> (2013)
Plant elicitor peptides (Peps)	Peptides	<i>Arabidopsis thaliana</i>	Defense gene activation, hydrogen peroxide accumulation, resistance against <i>Pythium</i> and <i>Pseudomonas</i>	Huffaker <i>et al.</i> (2006)
HMGB3	Proteins	<i>Arabidopsis thaliana</i>	MAPK activation, callose deposition, fungal disease resistance	Choi <i>et al.</i> (2016)
PIPs	Peptides	<i>Arabidopsis</i>	Amplification of	Hou <i>et al.</i> (2014)

DAMP Molecule	Molecule Class	Target Plant Species	Major Immune Responses	References
		<i>thaliana</i>	immune signaling and resistance against fungal and bacterial pathogens	
Oligogalacturonides (OGs)	Cell wall fragments	<i>Solanum lycopersicum</i> , <i>Vitis vinifera</i> , <i>Arabidopsis thaliana</i>	PR protein induction, phytoalexin synthesis, disease reduction	Ferrari <i>et al.</i> (2013)
Cellodextrins	Saccharides	<i>Vitis vinifera</i>	Calcium influx, PR gene activation, chitinase and glucanase induction	Aziz <i>et al.</i> (2007)
Cellobiose	Saccharides	<i>Arabidopsis thaliana</i>	MAPK activation, defense gene expression, suberin biosynthesis	Souza <i>et al.</i> (2017)
Cutin fragments	Cell wall derivatives	<i>Cucumis sativus</i> , <i>Solanum lycopersicum</i>	ROS production and enhanced defense responses	Fauth <i>et al.</i> (1998); Kauss <i>et al.</i> (1999)
Methanol	Cell wall derivatives	<i>Nicotiana benthamiana</i>	Enhanced resistance in neighboring plants against bacterial pathogens	Komarova <i>et al.</i> (2014)
Volicitin	Fatty-amino acid conjugates	<i>Zea mays</i> , <i>Glycine max</i>	VOC production, jasmonic acid and ethylene signaling	Alborn <i>et al.</i> (1997)
18:3-Gln	Fatty-amino acid conjugates	<i>Zea mays</i>	JA and ET signaling, activation of defense-related	Huffaker <i>et al.</i> (2013)

DAMP Molecule	Molecule Class	Target Plant Species	Major Immune Responses	References
			genes	

Abbreviations: ROS – Reactive oxygen species; MAPK – Mitogen-activated protein kinase; JA – Jasmonic acid; SA – Salicylic acid; ET – Ethylene; PR – Pathogenesis-related proteins; VOCs – Volatile organic compounds.

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LACTIC ACID BACTERIA: ENHANCING FOOD QUALITY AND SHELF LIFE NATURALLY

R. Gayathri¹, L. Vinoth Kumar^{2*}, G. Dhivagar¹, E. K. Devipriya¹,
M. Dhanu Pradeep¹ and S. T. Dhivya Bharathi¹

¹³⁴⁵⁶B.F.Sc Scholar, Department of Fish Processing Technology,
TNJFU- Dr.MGR. Fisheries College and Research Institute, Ponneri,
Thiruvallur District, Tamil Nadu 601204

²Assistant professor, Department of Fish Processing Technology,
TNJFU - Fisheries College and Research Institute, Thoothukudi-628 008, Tamil Nadu.

*Corresponding Email: vinothkumar@tnfu.ac.in

Abstract

Food preservation is essential to maintain quality, safety, and shelf life, especially in the presence of microbial spoilage. Increasing concerns about synthetic preservatives have led to a growing interest in natural alternatives. Lactic acid bacteria (LAB), a group of beneficial microorganisms, play a significant role in food preservation through fermentation and bio preservation. They inhibit spoilage and pathogenic microorganisms by producing organic acids, antimicrobial compounds, and through competitive exclusion. In addition to preservation, LAB improve nutritional value, sensory quality, and provide health benefits. This article discusses the role of LAB in food preservation, including their mechanisms, applications, advantages over chemical preservatives, and their importance in modern food systems.

Keywords: Lactic acid bacteria (LAB), food preservation, fermentation, biopreservation, antimicrobial activity, bacteriocins, acidification, food safety, probiotic bacteria, natural preservatives, shelf life extension, fermented foods, clean-label foods, microbial inhibition, sustainable food systems.

Introduction to Food Preservation and Microbial Challenges

Food spoilage is primarily caused by microorganisms such as bacteria, yeasts, and molds that degrade food components, leading to loss of quality and safety. Traditional preservation methods like drying, salting, and refrigeration have been widely used; however, the increasing demand for safe, natural, and minimally processed foods has encouraged the use of biological preservation methods. Among these, lactic acid bacteria (LAB) have gained significant attention due to their effectiveness and safety.

What are Lactic Acid Bacteria (LAB)?

Lactic acid bacteria (LAB) are a group of Gram-positive, non-spore-forming microorganisms that produce lactic acid as the main product of carbohydrate fermentation. They are naturally present in milk, vegetables, and the human gut. Common genera include *Lactobacillus*, *Lactococcus*, *Leuconostoc*, and *Pediococcus*. LAB are generally recognized as safe (GRAS) and have been used for centuries in traditional fermentation processes. Their ability to convert sugars into lactic acid and other beneficial compounds makes them highly valuable in food preservation and processing.

Mechanisms of Food Preservation by Lactic Acid Bacteria

The preservative action of lactic acid bacteria is based on multiple complementary mechanisms. One of the primary mechanisms is acidification. During fermentation, LAB produce lactic acid,

which lowers the pH of the food. This acidic environment inhibits the growth of spoilage organisms and pathogenic bacteria, thereby enhancing food safety. In addition to acid production, LAB synthesize antimicrobial compounds such as bacteriocins, hydrogen peroxide, and other organic acids. These substances actively suppress or eliminate harmful microorganisms. Another important mechanism is competitive exclusion, where LAB rapidly utilize available nutrients and occupy space, limiting the growth of undesirable microbes. Furthermore, certain LAB strains have the ability to reduce toxins such as mycotoxins and interfere with the activity of pathogens. The combination of these mechanisms makes LAB an efficient and reliable natural preservation system.

Types of Foods Preserved by LAB

Lactic acid bacteria are widely used in the preservation of various food products. In dairy processing, they are essential for the production of yogurt, cheese, and buttermilk, contributing to both preservation and desirable sensory characteristics. In vegetable fermentation, LAB are responsible for the stability and flavor of products such as pickles, sauerkraut, and kimchi. They are also used in meat and fish products, including fermented sausages, where they help maintain safety and extend shelf life. In cereal-based foods, such as sourdough bread and fermented batters used for idli and dosa, LAB improve digestibility and nutritional quality. These applications demonstrate the versatility and importance of LAB in diverse food systems.

Benefits of Using LAB in Food Preservation

The use of lactic acid bacteria offers several advantages over conventional preservation methods. One of the most significant benefits is their natural origin, which aligns with consumer preferences for minimally processed foods. LAB provide a safe and effective alternative to synthetic preservatives, reducing potential health concerns. Additionally, LAB enhance food safety by inhibiting pathogenic microorganisms and reducing the risk of foodborne diseases. They also improve nutritional quality by increasing the availability of vitamins and enhancing digestibility. Their role in developing desirable flavours and textures further adds to their value in food production.

LAB vs Chemical Preservatives

Compared to chemical preservatives, LAB offer a safer and more sustainable approach to food preservation. Chemical preservatives may have potential health concerns and are often avoided by consumers seeking natural foods. In contrast, LAB are naturally occurring and contribute positively to both food safety and health. While chemical preservatives act by directly inhibiting microbial growth, LAB provide a multi-functional approach, including acidification, antimicrobial production, and nutritional enhancement. As a result, LAB are increasingly preferred in the production of clean-label and minimally processed foods.

Role of LAB in Modern Food Industry

In the modern food industry, LAB are widely used as starter cultures to ensure consistent fermentation and product quality. They play a key role in the production of dairy products, fermented foods, and beverages. The concept of **bio preservation**, which involves the use of natural microorganisms to extend shelf life, has gained importance. LAB are central to this approach due to their ability to control microbial growth naturally. With increasing consumer demand for natural and sustainable food products, the application of LAB continues to expand in industrial food processing.

Conclusion

Lactic acid bacteria represent a natural and effective solution to the challenges of food preservation. Through their ability to inhibit harmful microorganisms, enhance nutritional value, and improve sensory quality, they provide a balanced approach to maintaining food safety and quality. Their long-standing use in traditional foods, combined with their expanding role in modern food technology, highlights their significance in both past and future food systems. As the focus on natural and sustainable food production increases, LAB will continue to serve as essential contributors to safe and healthy food.

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ROLE OF WATER HYACINTH (*Eichhornia crassipes*) IN BIOREMEDIATION OF POLLUTED WATER BODIES

E. K. Devipriya, L. Vinoth Kumar, G. Dhivagar, M. Dhanu Pradeep, R. Gayathri and S. T. Dhivya Bharathi

^{1 3 4 5 6}B.F.Sc Scholar, Department of Fish Processing Technology, TNJFU- Dr.MGR. Fisheries College and Research Institute, Ponneri, Thiruvallur District, Tamil Nadu 601204

²Assistant professor, Department of Fish Processing Technology, TNJFU - Fisheries College and Research Institute, Thoothukudi-628 008, Tamil Nadu.
Corresponding Email: vinothkumar@tnfu.ac.in

Abstract

Water pollution is a growing environmental challenge in India, affecting the quality of rivers, lakes, and other water bodies. Bioremediation offers an eco-friendly approach to address this issue by using natural organisms to remove contaminants. The aquatic plant *Eichhornia crassipes* plays an important role in this process due to its rapid growth and extensive root system. Its roots act as a natural filter, absorbing pollutants, heavy metals, and excess nutrients such as nitrogen, phosphorus, ammonia, nitrates, and nitrites from contaminated water. By reducing these pollutants and supporting microbial activity around its roots, water hyacinth helps improve water quality, making it a simple and sustainable solution for treating polluted water bodies.

Introduction

Water pollution is a major environmental challenge in India. Although the country has nearly 4 % of the world's freshwater resources, about 70 % of its surface water is considered polluted due to untreated sewage, industrial discharge, and agricultural runoff, according to reports from the Central Pollution Control Board. Contaminated water is responsible for nearly 21 % of communicable diseases, affecting millions of people. In Tamil Nadu, water scarcity and pollution occur simultaneously, as the state has only about 3 % of India's water resources while supporting nearly 6 % of the population. Many rivers and urban water bodies monitored by the Tamil Nadu Pollution Control Board are affected by untreated sewage and industrial effluents. Because of these growing pollution problems, there is an increasing need for low-cost and natural remediation methods to improve water quality. One such promising natural solution is the aquatic plant *Eichhornia crassipes*, which has the ability to absorb pollutants and help clean contaminated water bodies through biological processes.

Water Hyacinth In Cleaning Polluted Water

The aquatic plant *Eichhornia crassipes* is widely studied for its ability to clean polluted water through natural biological and physical processes. These dense, fibrous roots dangle in the water and act like a living filtration network, capturing pollutants, heavy metals, nutrients, and suspended solids as water flows through them. Pollutants are first adsorbed onto the root surfaces, where they stick due to interactions with chemical groups on the plant tissue. Then many of these contaminants are taken into the plant's tissues through absorption, meaning they move from the water into the roots and stems of the plant where they accumulate. This process removes harmful substances from the water itself. Water hyacinth also promotes cleanup by

supporting microbial communities around its roots. Beneficial bacteria and microbes naturally colonize the root zone and help break down organic contaminants such as nitrogen-rich compounds and some toxic organic chemicals, further improving water quality. Because the plant grows rapidly and produces large amounts of biomass, it can treat large volumes of water over time, making it especially useful in constructed wetlands and wastewater treatment ponds where contaminated water remains in contact with the plants for days or weeks. In addition to removing nutrients like nitrogen and phosphorus that cause algal blooms, water hyacinth has been shown in studies to absorb heavy metals and other toxic elements, storing them within plant tissues and significantly lowering their levels in the surrounding water.

Pollutants Removed By Water Hyacinth

Water hyacinth (*Eichhornia crassipes*) is more than just a fast-growing water plant – it acts like a living water purifier by removing a wide range of nutrients and pollutants from polluted water through natural biological and physical processes. One of its most important roles is in reducing nutrient pollution. Water hyacinth takes up nitrogen compounds such as ammonia, nitrates, and nitrites, as well as phosphorus, which often enter water bodies from agricultural runoff and sewage. By absorbing these nutrients into its roots and stems, the plant helps prevent algal blooms and eutrophication situations where excess nutrients cause oxygen depletion, harming fish and aquatic life. Beyond nutrients, water hyacinth is effective at removing heavy metals such as zinc, chromium, lead, and iron from contaminated water, storing these toxic elements in its tissues and reducing their concentrations in the water column. These heavy metals come from industrial effluents, mining runoff, and urban pollution. The plant also helps to capture organic pollutants such as dyes and other industrial chemicals through adsorption, where molecules stick to the surface of the roots. Some research shows that its roots can bind and retain microplastics and other fine particles floating in water, contributing further to cleanup. Water hyacinth's combined ability to absorb nutrients, heavy metals, organic compounds and even tiny plastic particles makes it a powerful, natural tool for improving water quality in lakes, ponds and wastewater treatment systems especially in places where other treatments may be costly or unavailable.

Applications of Water Hyacinth on Waste Water Treatment

Water hyacinth (*Eichhornia crassipes*) has found an important role in wastewater treatment because it naturally removes key nutrients and improves water quality. When free-floating water hyacinths are placed in treated sewage or effluent ponds, their roots absorb dissolved pollutants directly from the water. Two important nutrients that often cause pollution – phosphorus, ammonia and nitrogen – are taken up efficiently by these plants as they grow, reducing the concentration of these components in the water over time. In controlled systems, larger decreases in total phosphorus are observed with longer water retention times, and ammonia nitrogen removal also increases significantly when water is in contact with the plants for longer periods. This nutrient uptake not only improves water clarity but also reduces the risk of downstream problems such as algal blooms and oxygen depletion. As water hyacinth grows, it produces significant biomass, which can be harvested periodically, helping to maintain its cleansing action. Because it grows rapidly, tolerates nutrient-rich environments, and does not require complex machinery, water hyacinth can be a low-cost, nature-based option for enhancing secondary treatment of wastewater before discharge or reuse.

Water Hyacinth: A Simple Solution To A Complex Problem

Water hyacinth offers a simple and natural answer to the complex challenge of polluted water. This fast-growing aquatic plant does more than just float on the surface — its extensive root system

actively removes nutrients such as phosphorus and ammonia nitrogen from wastewater, which are major contributors to eutrophication and harmful algal blooms. As these nutrients are taken up by the plant, water quality improves, oxygen levels stabilize, and the risk of downstream ecological damage decreases. Beyond nutrient uptake, the plant supports helpful microbial communities around its roots that further break down organic contaminants, creating a combined cleansing effect. Because water hyacinth thrives in nutrient-rich environments and does not require advanced technology to work, it presents a cost-effective, eco-friendly, and accessible tool that communities can use to enhance wastewater treatment. By harnessing nature's own mechanisms, water hyacinth transforms a troublesome invasive species into a practical ally for healthier, cleaner water.

Conclusion

Water pollution remains one of the major environmental concerns today, affecting the health of ecosystems and human communities. In this context, bioremediation offers a sustainable and nature-based solution for restoring polluted water bodies. The aquatic plant *Eichhornia crassipes*, commonly known as water hyacinth, plays a significant role in this process due to its rapid growth and extensive root system. Its roots act like a natural filtration network that absorbs excess nutrients such as nitrogen, ammonia, nitrates, nitrites, and phosphorus, along with heavy metals like zinc, chromium, lead, and iron from contaminated water. By removing these pollutants and supporting beneficial microbial activity around its roots, water hyacinth helps improve water quality in lakes, ponds, and wastewater treatment systems. This natural ability makes it a low-cost, eco-friendly, and accessible option for managing water pollution, especially in regions where advanced treatment technologies may not be available. When properly managed and harvested, water hyacinth can transform from a problematic invasive plant into a valuable resource for environmental restoration and sustainable water management.

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PLANNING PRECISE FIELD EXPERIMENTS WITH TWO-WAY BLOCKING

Archana A^{1,2*}, Sukanta Dash², Anil Kumar³ and Vankudoth Kumar^{1,2}

¹The Graduate School, ICAR-Indian Agricultural Research Institute,
New Delhi-110012, India

²ICAR-Indian Agricultural Statistics Research Institute,
Pusa, New Delhi-110012, India

³Krishi Bhavan, Indian Council of Agricultural Research,
New Delhi-110001, India

*Corresponding Email: archanamscagri19@gmail.com

Abstract

Mixed-level factorial experiments allow crop researchers to study practices that naturally have different numbers of options, such as three varieties, two irrigation methods and three nitrogen rates. Their usefulness, however, depends on a field layout that separates treatment effects from fertility and moisture variation. Two-way blocking known as row-column designs control variation in two directions at the same time. Using one maize example, this article shows how the MFRCD R package can generate a 6×6 layout for 18 treatment combinations with two replications. The illustrated layout distributes every variety, irrigation method and nitrogen rate evenly across rows and columns. Simple software checks before planting help researchers obtain more precise comparisons and convert experimental results into location-specific recommendations for farmer.

Keywords: Mixed-level factorial experiment; Row-column design; Field variability; MFRCD; Maize trial

Introduction

Farm recommendations are rarely based on one input alone. Crop performance is usually shaped by a combination of variety, water supply, fertilizer, sowing time and crop protection. A factorial experiment studies such factors together and reveals whether the response to one practice changes with another. When the factors have unequal numbers of levels, the experiment is called mixed-level or asymmetrical. This structure is practical because researchers can test only the options that are agronomically meaningful rather than forcing every factor to have the same number of levels.

Why a row-column layout is needed

A field may change from east to west because of soil fertility and from the upper to the lower side because of slope, drainage or irrigation movement. Ordinary blocking usually controls one direction. A row-column design treats rows and columns as two blocking directions, so both sources of nuisance variation can be adjusted during analysis. The aim is not simply to make a neat field map; it is to protect comparisons among main effects and useful interactions, such as variety $\times$ nitrogen or irrigation $\times$ nitrogen (Godolphin 2019; Yadav et al. 2026).

Practical example: a maize management trial

Suppose a researcher wants to identify a maize package for fields with limited irrigation water. The trial includes three varieties, two irrigation methods and three nitrogen rates. Multiplying the factor levels gives $3 \times 2 \times 3 = 18$ treatment combinations. Two replications require 36 plots, which can be arranged as six rows and six columns.

Table 1. Factors and treatment levels in the maize example

Factor	Levels	Codes	Meaning
Variety (V)	3	V1–V3	Three locally relevant maize varieties
Irrigation (I)	2	I1, I2	I1: furrow; I2: drip irrigation
Nitrogen (N)	3	N1–N3	80, 120 and 160 kg N/ha

The field layout should spread these factor levels across both directions. In the illustrated design, each row and each column contains two plots of every variety, three plots under each irrigation method and two plots at each nitrogen rate. This balance makes treatment comparisons less dependent on where a plot happens to lie in the field.

Generating the design with the MFRCD R package

Manual construction becomes difficult as the number of factors increases. The MFRCD package (Archana and Dash 2026) provides functions for constructing, checking, analysing and, when necessary, repairing mixed-level factorial row-column designs. For the maize example, the following commands generate a direct design and check its main statistical properties.

```
install.packages("MFRCD")
library(MFRCD)

maize_rcd <- mfrcd(levels = c(3, 2, 3),
  sep = "-", prefer = "direct")
maize_check <- verify_mfrcd(maize_rcd,
  levels = c(3, 2, 3),
  sep = "-", max_order = 2)

maize_rcd
maize_check
```

The package uses zero-based treatment labels in its generated matrix. For field use, the labels can be renamed as V1–V3, I1–I2 and N1–N3. The 6 × 6 arrangement below is the same direct construction shown with agronomic labels. Each of the 18 combinations occurs twice.

MFRCD layout for a 3 × 2 × 3 maize experiment

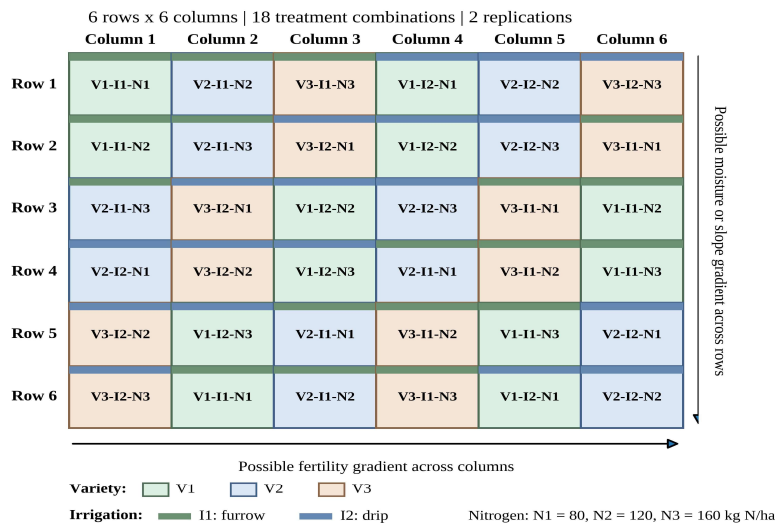


Figure 1. MFRCD layout for the 3 × 2 × 3 maize experiment.

Codes:
V = variety,
I = irrigation and
N = nitrogen rate.
Source: author-generated illustration using the direct MFRCD construction.

How to use the layout correctly

The printed matrix is a statistical layout, not the final randomization record. Before planting, the researcher should decide which physical direction represents rows and columns, then randomize row order, column order or treatment positions in a manner consistent with the design. The final field map must be saved. Uniform plot size, border rows, irrigation delivery and observation procedures remain essential; software cannot correct poor field execution.

What should be checked before planting?

A visually balanced design is not automatically adequate. The verification output should be examined for connectedness, replication, row and column balance, estimability of the required effects and efficiency. The priority effects must be specified in advance. For this example, the researcher may wish to protect variety, irrigation and nitrogen main effects and the variety $\times$ nitrogen and irrigation $\times$ nitrogen interactions. Candidate layouts should be compared before a field is marked.

- Use realistic factor levels that farmers can adopt and that equipment can deliver accurately.
- Align rows and columns with the two strongest field gradients identified during site inspection.
- Record yield together with water use, fertilizer cost, crop duration and production risk.
- Validate promising combinations across seasons, locations or farmers' fields before recommendation.

Turning the results into a farmer-ready message

The main value of the experiment is not a single overall winner. The analysis can reveal, for example, whether a variety maintains yield under furrow irrigation, whether extra nitrogen is profitable only with drip irrigation, or whether a moderate nitrogen rate gives a safer return under limited water. Such interaction-based results support recommendations for specific production situations rather than one blanket package for every farmer.

Conclusion

Row-column designs make mixed-level factorial trials more reliable when field variability occurs in two directions. In the maize example, MFRCD converts 18 treatment combinations into a balanced 6×6 layout with two replications and provides tools for checking the design before implementation. When combined with proper randomization, careful field management and multi-location validation, the approach can produce precise and practical crop-management recommendations.

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RECIRCULATING AQUACULTURE SYSTEMS (RAS): THE FUTURE OF SUSTAINABLE FISH FARMING

Tandel Sakshikumari Gunvantbhai

College of Fisheries Science, Veraval

Corresponding Email: vivektandel3232@gmail.com

Abstract

Aquaculture has emerged as one of the fastest-growing food production sectors worldwide, playing a crucial role in ensuring food security, nutrition, and economic development. However, conventional aquaculture systems often face challenges such as excessive water consumption, environmental pollution, disease outbreaks, and limited land availability. Recirculating Aquaculture Systems (RAS) have emerged as an innovative and sustainable solution that enables intensive fish production with minimal water use and improved environmental control. RAS continuously treats and reuses water through a series of mechanical, biological, and disinfection units, maintaining optimal water quality for fish growth while reducing water exchange and waste discharge. The system offers several advantages, including enhanced biosecurity, efficient resource utilization, high stocking density, year-round production, and reduced environmental impacts. Integration of automation, artificial intelligence (AI), sensors, and Internet of Things (IoT)-based monitoring has further improved the efficiency of RAS. This article discusses the concept, components, working principles, advantages, and significance of Recirculating Aquaculture Systems in promoting sustainable and profitable fish farming.

Keywords: Recirculating Aquaculture System, RAS, Sustainable Aquaculture, Fish Farming, Water Quality, Biosecurity, Precision Aquaculture.

Introduction

Aquaculture currently supplies more than half of the aquatic animals consumed globally and continues to expand rapidly in response to increasing demand for fish protein and declining capture fisheries (FAO, 2024). However, traditional aquaculture systems require large quantities of water and land while generating nutrient-rich effluents that may adversely affect surrounding aquatic ecosystems. Furthermore, climate change, water scarcity, disease outbreaks, and environmental regulations have created additional challenges for sustainable aquaculture development (FAO, 2022). To overcome these limitations, Recirculating Aquaculture Systems (RAS) have emerged as one of the most advanced aquaculture technologies. RAS enables intensive fish production by continuously treating and reusing culture water through mechanical filtration, biological filtration, aeration, and disinfection processes. Unlike conventional pond or flow-through systems, RAS minimizes water consumption while maintaining excellent water quality under controlled environmental conditions (Timmons & Ebeling, 2010). The increasing demand for sustainable food production, efficient resource utilization, and environmentally friendly farming practices has accelerated the adoption of RAS worldwide. The technology is now widely used for the commercial production of high-value fish species such as tilapia, rainbow trout, Atlantic salmon, barramundi, catfish, and ornamental fishes. Modern RAS facilities also incorporate digital technologies such as water quality sensors, automated feeders, artificial intelligence (AI), and Internet of Things (IoT)-based monitoring systems, making fish farming more efficient and precise (Martins et al., 2010).

Concept of Recirculating Aquaculture Systems (RAS)

A Recirculating Aquaculture System (RAS) is a land-based intensive fish farming system in which culture water is continuously treated, purified, and reused rather than being discharged after a single use. The system removes suspended solids, toxic nitrogenous wastes, excess carbon dioxide, and harmful microorganisms before returning clean water to the culture tanks (Lekang, 2019). Typically, only 1–10% of the total system water is replaced daily to compensate for evaporation, sludge removal, and maintenance. Consequently, RAS can reduce water consumption by more than 90% compared with conventional aquaculture systems, making it particularly suitable for regions experiencing water scarcity (FAO, 2022). The primary objective of RAS is to create a stable and controlled aquatic environment that maximizes fish growth, feed efficiency, survival, and productivity while minimizing environmental impacts. Continuous monitoring and management of water quality parameters such as temperature, dissolved oxygen, pH, ammonia, nitrite, nitrate, and carbon dioxide are essential for successful operation.

Major Components of RAS

The efficiency of a Recirculating Aquaculture System depends on the proper functioning of several integrated treatment units. Each component performs a specific role in maintaining optimum water quality and fish health.

Culture Tank

The culture tank is the primary unit where fish are reared. Circular tanks are most commonly used because they facilitate uniform water circulation, efficient waste removal, and better fish distribution. Tanks are generally constructed from fiberglass, concrete, high-density polyethylene (HDPE), or reinforced plastic materials depending on production scale and cultured species (Timmons & Ebeling, 2010).

Mechanical Filtration

Mechanical filters remove suspended solids such as uneaten feed, fish feces, and organic debris before they decompose and deteriorate water quality. Common mechanical filtration systems include drum filters, screen filters, settling tanks, and swirl separators. Efficient removal of solid waste reduces oxygen demand, improves water clarity, minimizes microbial growth, and enhances the overall performance of the biological filtration system.

Biological Filtration

Biological filtration is the heart of every RAS because it removes toxic nitrogenous wastes generated from fish metabolism. Beneficial nitrifying bacteria colonize the biofilter media and convert toxic ammonia (NH_3) into nitrite (NO_2^-), followed by conversion of nitrite into relatively less toxic nitrate (NO_3^-) through the process of nitrification (Lekang, 2019). Common biofilter media include plastic beads, moving bed biofilm reactors (MBBR), fluidized sand filters, and fixed-bed biofilters. Maintaining an efficient biofilter is essential for fish survival, particularly under high stocking densities.

Aeration and Oxygenation

Fish continuously consume dissolved oxygen for respiration, making oxygen management one of the most critical aspects of RAS operation. Aeration systems increase dissolved oxygen concentration while simultaneously removing excess carbon dioxide produced during respiration. Pure oxygen injection systems, oxygen cones, diffused aeration, venturi injectors, and low-head oxygenators are commonly used in commercial RAS facilities to maintain optimum oxygen concentrations and support intensive fish production (Martins et al., 2010).

UV Sterilization and Ozone Treatment

Ultraviolet (UV) sterilizers and ozone generators are incorporated into RAS to improve biosecurity and reduce pathogen loads. UV radiation inactivates bacteria, viruses, fungi, and protozoa by damaging their genetic material, whereas ozone oxidizes organic compounds and improves water clarity. These disinfection systems significantly reduce disease transmission while minimizing dependence on antibiotics and chemical disinfectants (FAO, 2024).

Pumps and Plumbing System

Water pumps continuously circulate water through different treatment units within the system. A properly designed plumbing network ensures efficient movement of water between culture tanks, filters, aeration units, and disinfection systems. Reliable pumps with backup power systems are essential because interruption of water circulation may rapidly reduce dissolved oxygen levels and threaten fish survival.

Working Principle of RAS

The operation of a Recirculating Aquaculture System is based on continuous water purification and reuse. Water from the fish culture tanks first passes through the mechanical filter, where suspended solids such as feces and uneaten feed are removed. The partially purified water then enters the biological filter, where beneficial nitrifying bacteria convert toxic ammonia into nitrite and subsequently into nitrate through biological nitrification (Lekang, 2019). Following biological filtration, the water passes through degassing units to remove excess carbon dioxide and then enters the oxygenation system, where dissolved oxygen is restored to optimal levels. Finally, the water undergoes UV sterilization or ozone treatment to eliminate harmful microorganisms before being returned to the fish culture tanks. This continuous treatment cycle maintains excellent water quality, supports high stocking densities, conserves water resources, and creates a stable environment for fish growth.

Advantages of Recirculating Aquaculture Systems

Recirculating Aquaculture Systems offer numerous technical, environmental, and economic advantages over conventional aquaculture systems. Major advantages include:

- More than 90% reduction in water consumption.
- Year-round fish production under controlled environmental conditions.
- High stocking densities and increased productivity.
- Improved feed conversion efficiency (FCR).
- Better biosecurity and reduced disease transmission.
- Minimal environmental pollution due to reduced wastewater discharge.
- Efficient utilization of land and water resources.
- Easy monitoring and management of water quality.
- Lower dependence on climatic conditions.
- Compatibility with automation, AI, IoT, and precision aquaculture technologies.
- Improved product quality and enhanced market value.
- Sustainable production suitable for urban and water-scarce regions (FAO, 2024).

These advantages have made RAS one of the most promising technologies for future aquaculture, supporting sustainable fish production while minimizing environmental impacts.

Suitable Fish Species for RAS

Recirculating Aquaculture Systems (RAS) are suitable for culturing a wide range of freshwater, brackish water, and marine fish species. Species selected for RAS should possess fast growth, high

market demand, tolerance to intensive stocking, and the ability to thrive under controlled environmental conditions (Timmons & Ebeling, 2010). Common freshwater species cultured in RAS include:

- Nile tilapia (*Oreochromis niloticus*)
- Pangasius (*Pangasianodon hypophthalmus*)
- African catfish (*Clarias gariepinus*)
- Rainbow trout (*Oncorhynchus mykiss*)
- Common carp (*Cyprinus carpio*)
- Rohu (*Labeo rohita*)
- Ornamental fishes

Marine and brackish water species include:

- Atlantic salmon (*Salmo salar*)
- Asian seabass (*Lates calcarifer*)
- Cobia (*Rachycentron canadum*)
- Groupers (*Epinephelus* spp.)
- Turbot (*Scophthalmus maximus*)

The choice of species depends on water temperature, market demand, production objectives, availability of quality seed, and economic feasibility.

Water Quality Management

Water quality management is the most critical aspect of successful RAS operation because fish are cultured under intensive stocking conditions with limited water exchange. Continuous monitoring ensures a stable environment for fish growth and minimizes stress and disease outbreaks (Lekang, 2019). The major water quality parameters include:

- Temperature
- Dissolved oxygen (DO)
- pH
- Ammonia (NH₃)
- Nitrite (NO₂⁻)
- Nitrate (NO₃⁻)
- Carbon dioxide (CO₂)
- Alkalinity
- Water flow rate

Modern RAS facilities employ digital sensors, automated monitoring systems, and alarm-based control units to continuously assess these parameters. Early detection of water quality fluctuations enables timely corrective measures, ensuring high survival and production efficiency.

Biosecurity and Disease Control

Disease prevention is one of the major advantages of RAS because the system operates under highly controlled environmental conditions. Unlike open pond systems, RAS minimizes the entry of pathogens through restricted water exchange and controlled access to production units (Martins et al., 2010). Effective biosecurity practices include:

- Use of pathogen-free seed.
- Quarantine of newly introduced fish.
- Routine health monitoring.

- Regular cleaning and disinfection of tanks and equipment.
- UV sterilization and ozone treatment.
- Maintenance of optimal water quality.
- Restricted movement of personnel and equipment.
- Responsible use of therapeutics and antibiotics.

Maintaining strong biosecurity reduces mortality, improves fish welfare, minimizes economic losses, and enhances overall system sustainability.

Economic Importance of RAS

Although the initial investment required for RAS is higher than that for conventional aquaculture systems, the technology offers significant long-term economic benefits. Efficient water use, high stocking densities, improved survival, better feed conversion, and year-round production contribute to higher productivity and profitability (Badiola et al., 2012). RAS can be established near urban markets, thereby reducing transportation costs and ensuring the supply of fresh fish throughout the year. The technology also creates employment opportunities in hatchery management, system installation, engineering, feed production, water quality management, fish processing, and technical services. Government support, technological advancements, and increasing consumer demand for high-quality seafood are expected to improve the economic viability of RAS in the coming years.

Challenges and Limitations

Despite its numerous advantages, RAS faces several technical and economic challenges that limit its widespread adoption, particularly among small-scale farmers. Major constraints include:

- High initial capital investment.
- Expensive filtration and life-support equipment.
- High electricity consumption.
- Requirement for skilled technical personnel.
- Risk of rapid fish mortality during power failures.
- Regular maintenance of filtration systems.
- High operational and maintenance costs.
- Limited technical awareness among farmers.

These challenges can be minimized through proper training, reliable backup power systems, government support, and adoption of energy-efficient technologies. The major advantages and limitations of Recirculating Aquaculture Systems are summarized in Table 1.

Table 1. Advantages and Challenges of Recirculating Aquaculture Systems (RAS)

Aspect	Advantages	Challenges
Water Use	More than 90% water reuse	High dependence on filtration efficiency
Fish Production	High stocking density and year-round production	High initial investment
Water Quality	Continuous monitoring and control	Requires skilled management
Biosecurity	Reduced pathogen entry and disease risk	System failure may rapidly affect fish health
Environmental Impact	Reduced wastewater discharge and pollution	Disposal of concentrated sludge is required

Aspect	Advantages	Challenges
Feed Efficiency	Improved Feed Conversion Ratio (FCR)	High-quality commercial feed is essential
Automation	Compatible with AI, IoT, and smart sensors	Advanced technology increases operational cost
Market Benefits	High-quality fish production near urban markets	Reliable electricity supply is essential

Future Prospects

Recirculating Aquaculture Systems are expected to play a central role in the future of global aquaculture due to increasing water scarcity, urbanization, and the growing demand for sustainable food production (FAO, 2024). The integration of Artificial Intelligence (AI), Internet of Things (IoT), machine learning, cloud computing, and robotics is transforming RAS into a highly efficient precision aquaculture system. Automated feeders, smart sensors, real-time water quality monitoring, and AI-based disease detection improve production efficiency while reducing labour requirements. Future innovations are likely to focus on renewable energy integration, advanced biofiltration technologies, circular economy approaches, and improved waste recycling systems. These developments will further reduce production costs, improve environmental sustainability, and strengthen global food security.

Conclusion

Recirculating Aquaculture Systems (RAS) represent one of the most advanced and sustainable technologies for modern fish farming. By continuously treating and reusing water, RAS significantly reduces water consumption, improves biosecurity, minimizes environmental pollution, and supports intensive fish production under controlled conditions. The integration of efficient filtration systems, water quality monitoring, automation, and digital technologies enables farmers to achieve higher productivity, improved fish health, and better resource-use efficiency. Although high capital investment and technical expertise remain major challenges, continuous technological advancements and supportive government initiatives are making RAS increasingly accessible and economically viable. As global demand for fish continues to rise and freshwater resources become increasingly limited, RAS is expected to play a crucial role in ensuring sustainable aquaculture, food security, and climate-resilient fish production.

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SCAB, ALTERNARIA LEAF SPOT AND MARSSONINA BLOTCH IN APPLE: UNDERSTANDING AND MANAGING PREMATURE DEFOLIATION

Arun Kumar* and Durga Prashad Bhandhari

Regional Horticultural Research & Training Station and Krishi Vigyan Kendra,
Sharbo, Kinnaur, Himachal Pradesh, 172107

*Corresponding Email: arunkumar.negi@gmail.com



Apple growing in Himachal Pradesh has always depended on a fairly narrow and predictable window of temperature and moisture. That predictability is slipping. Over the past few seasons, orchards across the state, including the dry temperate belt of Kinnaur, have been receiving rain in short, intense bursts rather than the steady spells growers were once used to, often following long dry stretches. The shift has been good news for very few things and bad news for one thing in particular: foliar disease pressure. Scab, Alternaria leaf spot and Marssonina blotch, once manageable with routine sprays, are now showing up earlier, spreading faster and, in several orchards, triggering leaf fall well before the fruit has finished sizing. This is not a cosmetic problem. A tree that loses its canopy in July or August is a tree that has lost its manufacturing unit at the busiest point of the season. The purpose of this article is to lay out, in plain but scientifically accurate terms, what is causing this premature leaf fall, how the three diseases differ from one another, and what an orchardist can realistically do about it, drawing on published plant pathology literature as well as the current fungicide recommendations issued by the Department of Horticulture, Himachal Pradesh and Dr Y.S. Parmar University of Horticulture and Forestry, Nauni.

Why leaf loss costs more than it looks like

Leaves are not simply green cover; they are the tree's only source of manufactured sugars. Fruit size, colour, total soluble solids and storage life all trace back to how long and how efficiently the

canopy has been photosynthesising through the season. Equally important, and easy to overlook, is that the carbohydrate reserves built up in late summer are what the tree draws on to differentiate flower buds for the following year. Premature defoliation therefore rarely stays a one-season problem. An orchard that drops its leaves early in one year commonly carries a lighter, patchier bloom the next, and the effect can compound over consecutive bad years.

Three diseases, three distinct signatures

Apple Scab

Caused by the fungus *Venturia inaequalis*, scab announces itself on the underside of young leaves as small, olive-green, velvety lesions that darken to brown or black with age. Heavily infected leaves curl, yellow and drop early, and the same fungus produces rough, cracked, near-black lesions on fruit that make them unfit for the fresh market and poor candidates for storage. The pathogen overwinters as perithecia in leaf litter on the orchard floor; when spring rain wets these fallen leaves, ascospores are ejected into the air and carried onto emerging foliage, after which repeated cycles of conidial infection keep the disease moving through the canopy as long as leaves stay wet for extended periods.



Alternaria Leaf Spot and Blight



Alternaria leaf and fruit spot (ALFS), caused principally by *Alternaria mali* along with related species such as *A. alternata*, *A. arborescens* and *A. tenuissima*, has moved from being a minor nuisance to a serious economic problem in most apple-growing tracts over the last decade, with the Delicious group of cultivars showing particular susceptibility (Madhu et al., 2020). The disease begins as small, round, purplish-brown spots that enlarge and coalesce into irregular, frog-eye-like patches bordered by a purple margin.

Infection of petioles turns leaves yellow and brings on early defoliation, a process that becomes markedly worse where European red mite infestation is also present.

On fruit, small dark spots cluster around the lenticels and later expand into sunken, cracked lesions; damaged fruit in storage often develops a light grey surface mould and can slide into soft rot. The fungus penetrates through the cuticle, lenticels or existing wounds and, within roughly nine days under favourable conditions, produces necrotic lesions. A host-specific compound it secretes, known as AM-toxin, damages chloroplasts and cell membranes, disrupting



photosynthesis and respiration and accelerating cell death in susceptible tissue (Madhu et al., 2020).

Marssonina Leaf Blotch

Known to many growers simply as premature leaf fall disease, Marssonina blotch is caused by the fungus in its asexual stage, *Marssonina coronaria*, with *Diplocarpon mali* as the sexual stage. Symptoms start as small, dark green spots on mature, lower-canopy leaves that merge into larger, irregular blotches; under a hand lens these blotches show characteristic black fruiting bodies, which remain the most reliable



field diagnostic. Dark, sunken lesions can also appear on fruit. The fungus survives winter in fallen infected leaves and, once spring humidity climbs past roughly 80 percent at 20-22°C, spores are dispersed by wind and rain-splash to infect new foliage. Because the disease is polycyclic, a single favourable season can support several successive infection cycles, which is why it spreads so quickly once established.

When several pathogens act together

Field surveys across apple belts of Himachal Pradesh, including Shimla district, have increasingly found that leaf blotch symptoms are not always the work of a single organism. Fungi such as *Curvularia*, *Cladosporium*, *Colletotrichum gloeosporioides*, *Botryosphaeria* and *Pestalotiopsis* are frequently isolated alongside *Alternaria* and *Marssonina* from the same symptomatic tissue. Trees weakened by moisture stress after drought, nutrient imbalance, mite pressure, root rot or canker are more vulnerable to this kind of mixed infection, and once established, such trees act as reservoirs from which spores spread to otherwise healthy.

Disease Cycle and the Weather Connection

Disease	Causal organism	Favourable conditions	Primary source of inoculum
Apple scab	<i>Venturia inaequalis</i>	Cool, wet weather; prolonged leaf wetness	Ascospores released from perithecia on fallen leaves
<i>Alternaria</i> leaf and fruit spot	<i>Alternaria mali</i> and associated species	Around 25°C with relative humidity above 90%	Dormant mycelium in leaf litter, twigs and mummified fruit
Marssonina leaf blotch	<i>Marssonina coronaria</i> / <i>Diplocarpon mali</i>	Relative humidity above 80% with 20-22°C	Fruiting bodies on infected fallen leaves

The pattern across all three diseases is strikingly consistent: the primary source of inoculum sits in leaf litter on the orchard floor, waiting for spring moisture to release it. That single fact is what makes orchard sanitation the single highest-value intervention available to growers, ahead of any spray. Erratic post-drought rainfall, high humidity, poor air movement within a dense canopy and wide swings between day and night temperature all favour spore germination and infection, and this is exactly the pattern that has become more common across Himachal Pradesh's apple belt, including Kinnaur, in recent seasons.

Integrated Management**Cultural and Orchard-Floor Practices**

- Rake up and destroy fallen leaves, fruit and twigs at the end of the season; this single step removes the bulk of next year's inoculum before it ever has a chance to overwinter.
- Spray a 5 percent urea solution on fallen leaves on the orchard floor to hasten their decomposition and reduce fungal viability.
- Clear weeds and undergrowth to lower humidity within the canopy microclimate and improve air movement.
- Prune and thin in good time so that sunlight and air can reach the interior of the canopy, shortening the period leaves stay wet after rain or dew.
- Apply a copper-based fungicide within 24 hours of pruning to protect fresh cuts from secondary infection.
- Maintain balanced irrigation and nutrition; moisture-stressed and nutrient-deficient trees are consistently more susceptible to infection.
- Keep mite populations under check, since severe mite infestation has been shown to intensify *Alternaria*-related defoliation.

Chemical Management: What the HP Spray Schedule 2026 Recommends

The Spray Schedule Year 2026 (Apple), jointly issued by the Department of Horticulture, Himachal Pradesh and Dr Y.S. Parmar University of Horticulture and Forestry, Nauni, lays out a stage-wise fungicide programme aimed at scab, powdery mildew, *Alternaria* leaf spot/blight and premature leaf fall. At the tight cluster to pink bud stage, Dodine 65 WP (200 g), Difenoconazole 50 g/L SC or Hexaconazole 4% + Zineb 68% WP (500 g) give effective early cover against scab and powdery mildew. Through the fruit development period, combinations such as Metiram 55% + Pyraclostrobin 5% WG (200 g), Fluxapyroxad 250 g/L + Pyraclostrobin 250 g/L SC (50 mL) and Fluopyram 17.7% + Tebuconazole 17.7% w/w SC (126 mL) have proved particularly effective against *Alternaria* leaf spot, blight and premature defoliation. Twenty days after the walnut-size stage, Hexaconazole 4% + Zineb 68% WP (500 g) or Chlorothalonil 40% + Difenoconazole 4% (160 mL) hold both scab and *Alternaria* in check. In the pre-harvest window, 20 to 25 days before picking, Metiram 70% WG (600 g), Ziram 80% WP (500 g) or the Fluopyram-Tebuconazole combination help control late leaf fall and fruit rot. The schedule is emphatic on one further point: no fungicide should be tank-mixed with an unlisted insecticide, micronutrient or growth regulator, since such mixtures are a common and avoidable cause of fruit russetting and related disorders. It is worth noting how closely this state-level, field-tested schedule agrees with independent research. A review published by scientists at the ICAR-Central Institute of Temperate Horticulture, Srinagar, evaluating fungicides registered for *Alternaria* leaf and fruit spot control, rated combinations such as Fluxapyroxad + Pyraclostrobin, Difenoconazole + Cyprodinil, Pyraclostrobin + Boscalid, Metiram + Pyraclostrobin and Zineb + Hexaconazole among the most effective options available, with Mancozeb, Kresoxim methyl and Fluxapyroxad + Difenoconazole rated as good performers (Madhu et al., 2020). The overlap between the chemical groups recommended in that peer-reviewed evaluation and those prescribed in the HP spray schedule, principally SDHI-strobilurin combinations, triazoles and dithiocarbamates, is a useful cross-check for growers: it means the state recommendation is not just a bureaucratic default but is backed by fungicide-efficacy trials. Growers are advised to follow the current year's schedule rather than habit, rotate chemical groups to delay resistance build-up, and strictly observe the pre-harvest waiting period before picking so that the fruit reaching the market is residue-compliant.

Growth stage	Recommended fungicide (per 200 L water)	Disease targeted
Tight cluster to pink bud	Dodine 65 WP @ 200 g, or Hexaconazole 4% + Zineb 68% WP @ 500 g	Scab, powdery mildew, core rot
Fruit development	Metiram 55% + Pyraclostrobin 5% WG @ 200 g, or Fluxapyroxad + Pyraclostrobin SC @ 50 mL	Alternaria leaf spot/blight, premature leaf fall
20 days after walnut-size stage	Fluopyram + Tebuconazole SC @ 126 mL, or Hexaconazole + Zineb WP @ 500 g	Alternaria leaf spot, scab, premature leaf fall
Pre-harvest (20-25 days before harvest)	Metiram 70% WG @ 600 g, or Ziram 80% WP @ 500 g	Premature leaf fall, fly speck, fruit rot

Source: Spray Schedule Year 2026 (Apple), Department of Horticulture, Himachal Pradesh and Dr Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan. This is an abbreviated summary; growers should consult the full schedule for complete dosage, alternates and mixing restrictions before spraying.

A few operational cautions from the schedule are worth repeating in full, since they are often the difference between an effective spray and a wasted one:

- Never repeat the same fungicide in consecutive sprays; alternate chemical groups to slow the development of resistance.
- Do not mix Dodine with any other pesticide or chemical, avoid spraying it above 30°C or in slow-drying conditions, and never mix it with hard water.
- Keep at least a 15-day gap between a Captan spray and an oil spray, on either side, to prevent phytotoxic injury.
- In scab-prone orchards, hold a 12–14-day interval between sprays up to the primary scab stage, and repeat any spray washed off by heavy rain within seven days.

Building a Community Response

Fungal spores travel on wind and rain-splash without regard for boundary walls, which means a well-sprayed, well-sanitised orchard sitting next to a neglected one gains only partial protection. Sanitation and spray timing work best when neighbouring growers coordinate rather than act in isolation. Equally important is correct diagnosis: growers sometimes mistake a fungal blight for bacterial fire blight or vice versa, and treating one as the other wastes both money and time. Where symptoms are unclear, the nearest Krishi Vigyan Kendra, Horticulture Department office or university plant pathologist should be consulted before any treatment is finalised.

Conclusion

The apple belt of Himachal Pradesh, and high-altitude tracts such as Kinnaur in particular, are now dealing with a rainfall pattern that favours fungal foliar disease more often than it used to. Scab, Alternaria leaf spot/blight and Marssonina blotch share a common weakness that growers can exploit: all three overwinter in leaf litter on the orchard floor, which makes sanitation the cheapest and most effective first line of defence. No single spray solves premature defoliation on its own. What works, consistently, is the combination of orchard hygiene, balanced nutrition and irrigation, a properly rotated fungicide programme aligned with the current university and department recommendations, and regular field monitoring through the season. Growers who put these pieces together stand to protect not only this year's fruit quality and yield, but next year's bud formation and the orchard's productivity over the years that follow.

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CARBON SMART OLERICULTURE IN TROPICAL INDIA

Karakambadi Vaishnavi^{1*}, Syed Sadarunnisa² and Sangaraju Reddy Veera Nagaveni³

^{1*}PhD Scholar, Department of Vegetable Science,
Dr. Y.S.R. Horticultural University, College of Horticulture,
Anantharajupeta-516105, Andhra Pradesh, India

²Professor, Department of Vegetable Science,
Dr. Y.S.R. Horticultural University, College of Horticulture, Pulivendula-516390,
Andhra Pradesh, India

³PhD Scholar, Department of Vegetable Science, College of Agriculture – JNKVV

*Corresponding Email: vaishnavikarakambadi1998@gmail.com

Introduction

Tropical regions of India are increasingly experiencing high temperature stress, erratic rainfall patterns and progressive depletion of soil organic carbon, all of which threaten the sustainability of intensive vegetable production systems. Vegetable cultivation in these regions is characterized by small and fragmented landholdings, high cropping intensity, frequent irrigation and substantial fertilizer inputs leading to elevated greenhouse gas emissions particularly nitrous oxide from nitrogen misuse and declining soil health. Irrigation pressure, energy consumption and imbalanced nutrient management further increase the carbon footprint of vegetable systems. In this context, adopting carbon-smart olericulture becomes essential to enhance input-use efficiency, rebuild soil carbon stocks, reduce emission intensity and ensure sustainable vegetable productivity under the changing climatic scenario of tropical India Gouthami *et al.*, (2023).

Carbon Smart Olericulture

Carbon smart olericulture is an integrated production framework aimed at reducing the carbon footprint of vegetable cultivation while improving soil health, input efficiency, and adaptive capacity under changing climatic conditions.

Carbon Smart Strategies In Tropical Olericulture

Conservation Horticulture

Conservation horticulture is a key pillar of carbon-smart olericulture, emphasizing minimum tillage, residue retention, diversified crop rotation and the inclusion of cover crops in vegetable-based systems. By reducing soil disturbance and maintaining continuous soil cover this approach enhances soil organic carbon accumulation, improves soil structure, stimulates microbial activity and suppress nitrification and denitrification processes, leading to lower emission risks under suitable conditions. Residue retention and cover cropping protect the soil surface from erosion, moderate temperature fluctuations and reduce moisture loss through evaporation. Diversified crop rotations further enhance nutrient cycling and break pest and disease cycles. Collectively, these practices contribute to long-term soil health, improved moisture conservation, reduced input dependency and greater resilience of tropical vegetable production systems under climate variability.

Efficient Nutrient Management

Efficient nutrient management is a cornerstone of carbon-smart olericulture, integrating site-specific nutrient management, nano fertilizers, biofertilizers and integrated nutrient management

(INM) to optimize nitrogen use and minimize environmental losses. Site-specific approaches tailor fertilizer application to soil fertility status and crop demand, preventing excessive nitrogen accumulation that fuels nitrification and denitrification, the primary biological pathways responsible for N₂O emissions. Improved application methods such as banding, fertigation, split applications and targeted placement enhance nutrient uptake efficiency while minimizing losses. Nano fertilizers enhance nutrient delivery efficiency through controlled release and improved uptake, while biofertilizers such as nitrogen-fixing and phosphate-solubilizing microorganisms improve nutrient availability through biological processes. Integrated nutrient management, which combines organic and inorganic sources, supports balanced nutrient supply, enhances soil microbial activity and improves soil organic carbon status. These strategies synchronize nitrogen supply with crop demand, enhancing efficiency and reducing N₂O emissions Kesamreddy *et al.*, (2026).

Micro-irrigation and the water-carbon nexus

Micro-irrigation systems, particularly drip irrigation integrated with fertigation, represent a critical intervention in carbon-smart olericulture by enhancing water-use efficiency and optimizing nutrient delivery directly to the root zone. Precise water application reduces evaporation losses, limits leaching of nitrates and minimizes the anaerobic soil conditions that favour denitrification and N₂O emissions. Fertigation further synchronizes nutrient supply with crop demand, improving nutrient-use efficiency while reducing excess nitrogen accumulation in the soil. The adoption of solar-powered irrigation pumps lowers dependence on fossil fuel based energy sources, thereby directly reducing carbon dioxide emissions associated with irrigation. In protected cultivation systems, controlled irrigation combined with microclimate regulation enhances resource-use efficiency and stabilizes yields under climatic variability. Improved water management reduces energy use, lowers greenhouse gas emissions and enhances sustainability in intensive vegetable systems.

Soil carbon sequestration

Soil carbon sequestration is a fundamental component of carbon-smart olericulture, achieved through the application of compost, farmyard manure, biochar and green manuring to enhance soil organic carbon stocks. Organic amendments such as compost and farmyard manure supply labile and stable carbon fractions that promote aggregate formation and protect organic matter within soil microstructures, thereby stabilizing soil organic carbon against rapid decomposition. Biochar, owing to its recalcitrant carbon structure and high surface area, contributes to long-term carbon storage while improving cation exchange capacity and nutrient retention. Green manuring adds fresh biomass that stimulates microbial activity and enhances carbon inputs to the soil. Through these mechanisms soil organic carbon becomes stabilized, functioning as a carbon sink while simultaneously improving soil fertility, nutrient cycling and overall ecosystem resilience in intensive vegetable production systems Ilakiya *et al.*, (2024).

Climate-resilient varieties

The development and adoption of climate-resilient vegetable varieties constitute a vital component of carbon-smart olericulture, particularly under the increasing temperature extremes and water scarcity prevalent in tropical regions. Heat-tolerant genotypes maintain cellular stability, reproductive success and enzymatic efficiency under elevated temperatures, thereby sustaining yield. Physiological traits such as efficient stomatal regulation enable plants to balance carbon assimilation with transpiration, reducing excessive water loss while maintaining CO₂ uptake.

Varieties exhibiting higher photosynthetic rates enhance carbon fixation efficiency, contributing to greater biomass production and potentially higher soil carbon inputs. Improved water-use efficiency, defined as the ratio of carbon assimilated per unit of water transpired, further strengthens resilience under moisture-limited conditions. Collectively, these physiological adaptations not only stabilize productivity under climatic stress but also contribute to reduced emission intensity per unit yield, aligning varietal improvement with climate mitigation and sustainability goals.

Ethnic leafy greens under regenerative systems

Ethnic leafy greens such as *Amaranthus*, *Chenopodium*, colocasia leaves, and moringa represent promising components of regenerative olericulture due to their low external input requirements, short growth duration, and adaptation to local agro-climatic conditions. These crops typically exhibit high nutrient density and rapid biomass accumulation, enabling efficient carbon assimilation within short production cycles. Their relatively lower fertilizer dependency reduces the risk of excessive nitrogen application and associated N₂O emissions, while their quick turnover supports continuous ground cover and organic residue return to the soil. When cultivated under regenerative practices such as organic amendments, minimal tillage and diversified rotations these leafy vegetables can enhance soil organic carbon, stimulate microbial activity and improve nutrient cycling. Consequently, their production systems may demonstrate lower emission intensity (kg CO₂-eq per unit yield) compared to high-input fruit vegetables, aligning well with the principles of carbon-smart and regenerative olericulture in tropical environments Vaishnavi *et al.*, (2023).

Conclusion

Carbon Smart Olericulture offers a transformative pathway for sustaining vegetable production under the dual pressures of climate change and rising food demand. In tropical production systems characterized by high input intensity, declining soil organic carbon and increasing climatic variability, conventional approaches are no longer sufficient to ensure long-term productivity and environmental stability. By lowering emission intensity per unit yield and strengthening soil-plant-microbial interactions, carbon-smart strategies simultaneously address mitigation, adaptation and productivity goals. Transitioning toward such integrated systems is therefore essential not only for reducing the carbon footprint of vegetable cultivation but also for ensuring nutritional security, farmer livelihoods, and ecological sustainability in tropical India.

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Fig.1. Conservation horticulture through organic mulching in vegetable production



Fig.2. Drip irrigation for efficient water management in vegetable crops



Fig.3. Protected cultivation for climate-resilient vegetable production



Fig.4. Diverse leafy vegetables for regenerative and low-carbon olericulture

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SCREENING AND IDENTIFICATION OF SOURCES OF RESISTANCE AGAINST LEAF BLIGHT OF KODO MILLET CAUSED BY *Alternaria tenuissima*

**Alex Khalkho^{1*}, A. K Jain², Manisha Shyam³,
Devkumar Sareyam⁴ and Sanjay Kanth S. A⁵**

¹Ph.D. Scholar, Department of Plant Pathology, College of Agriculture,
GB Pant University of Agriculture and Technology,
Pantnagar (263145) Uttarakhand, India.

²Professor, Department of Plant Pathology, College of Agriculture,
Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur – 482004, India.

³Scientist, AICRP on Small Millets, RARS, Dindori – 481880, India.

⁴M.Sc. Scholar, Department of Horticulture, College of Agriculture,
Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur – 482004, India.

⁵Ph.D. Scholar, Department of Agronomy, College of Agriculture,
GB Pant University of Agriculture and Technology, Pantnagar (263145) Uttarakhand, India.
Corresponding Email: alexkhalkho2306@gmail.com

Abstract

An experiment was conducted in the field of Regional Agriculture Research Station, Dindori under Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (Madhya Pradesh). The study evaluated kodo millet cultivars for resistance of leaf blight, an emerging and critical disease for resource-limited farmers. Testing 14 cultivars in KIAVT and 21 cultivars in NSN revealed no complete resistance. However, KMV 582, IIMR KM 8, and JK 137 in KIAVT and RPS 868-1 in NSN showed resistance. Thirteen cultivars were moderately resistant and 15 were susceptible, with 3 highly susceptible cultivars. Previous research identified some resistant sources, but recent findings varied, notably for RK 390-25, which displayed inconsistent resistance levels across studies. The present study showed 4 resistant cultivars showed resistance in Bengaluru, while KMV 582, IIMR KM 8, and JK 137 showed moderate resistance in Nandyal. Confirming consistency, KMV 582 and IIMR KM 8 were also resistant in Mandya and RK 390-25 was consistently moderately resistant across above mentioned locations.

Keywords: kodo millet, *Alternaria tenuissima*, leaf blight, screening, resistant.

Introduction

Kodo millet (*Paspalum scrobiculatum* L.) an ancient crop which was originated in Africa but was domesticated in India about 3000 years ago (de Wet *et al.*, 1983). This particular crop is major member of 'Sri Anna' belongs to the family Poaceae with chromosome number $2n=4x=40$. Primarily the crop is grown in India but besides India it is also grown in Thailand, Vietnam, Bangladesh, Myanmar, Indonesia, Philippines and western parts of Africa. In India, the crop is largely grown in the states of Madhya Pradesh, Tamil Nadu, Telangana, Maharashtra, Gujarat, Karnataka, Chhattisgarh, Uttar Pradesh and Jharkhand (Hariprasanna, 2023). The crop faces a lot of diseases which is incited by number of pathogens like bacteria, fungi, viruses, etc. Among fungal pathogens, *Sporisorium paspali thunbergii* (Head smut), *Rhizoctonia solani* (Banded leaf blight), *Puccinia substriata* (Rust), *Ephelis oryzae* (Udbatta), *Alternaria alternata* (leaf blight) and several

species of *Helminthosporium* were reported to infect kodo millet and can even cause significant huge economic loss in grain yield under favourable environmental conditions (Jain and Sharma, 2010). Among the foliar disease encountered, leaf blight of kodo millet caused by *A. tenuissima* is a major and emerging constraint in the production and yield of kodo millet (Nagaraja *et al.*, 2016). However, research on the identification of resistant sources of kodo millet cultivars using screening techniques is meagre. Screening of kodo millet cultivars is an important step in management of the disease especially to the resource limited farmers. The aim of this research is to identify the resistant sources of kodo millet through screening technique.

Materials and method

An experiment was carried out in the field of Regional Agriculture Research Station, Dindori (22.95°N 81.08°E) for the screening of kodo millet against the leaf blight disease caused by *Alternaria tenuissima*. Two sets of kodo millet cultivars were received from the project coordinating unit (PC unit) of small millets, Bengaluru. These were screened under Kodo millet Initial and Advance Varietal Trial (KIAVT) and National Screening Nursery (NSN) in the experimental area of All India Coordinated Research Project on Small Millets, Regional Agricultural Research Station, Dindori (M.P.) during *Kharif* 2023. In KIAVT, 12 kodo millet and in NSN 19 cultivars along with one resistant check (RK 390-25) and one susceptible check (JK 76) were sown on 7th July, 2023 in two rows of 3.0 m length plot with 22.5 cm row to row and 10.0 cm plant to plant distance. The experiment was laid in randomized block design (RBD) with three replications. Recommended doses of fertilizers *i.e.*, 40 kg N and 20 kg P₂O₅ per hectare (ha⁻¹) was applied. Half of N₂ was given as basal dose along with full phosphorus before sowing. Remaining half quantity of nitrogen was given as top dressing 25 days after sowing (DAS). Ten plants of each cultivar from each replication were randomly selected and tagged. Leaf blight severity was recorded in tagged plants before flowering as per 1-9 grade scale given by Hariprasanna *et al.*, (2023) and kodo millet cultivars were grouped in different categories of reaction.

Table 1: Disease rating scale (1-9 scale) for brown spot/ leaf blight (Hariprasanna *et al.*, 2023)

Score	Description	Disease reaction
1	<1% leaf area affected	Highly resistant
2	1-5% leaf area affected	Resistant
3	6-10 % leaf area affected	Resistant
4	11-20% leaf area affected	Moderately resistant
5	21-30% leaf area affected	Moderately resistant
6	31-40% leaf area affected	Susceptible
7	41-50% leaf area affected	Susceptible
8	51-75% leaf area affected	Highly susceptible
9	>75% leaf area affected	Highly susceptible

Results and discussions

Sources of resistance against leaf blight of kodo millet

Kodo millet Initial and Advance Varietal Trial (KIAVT)

Data depicted in Table 2 shows the leaf blight severity which was recorded in 14 cultivars of kodo millet screened under KIAVT. Significant variation among different cultivars for leaf blight incidence was recorded properly. Disease severity ranging from 4.9 to 48.8 per cent with a mean of 26.5 per cent was recorded minimum in KMV 582 followed by 8.7 per cent in IIMRKM 8 and 9.0 per cent in

JK 137; hence these were designated as resistant. Whereas severity was recorded maximum in JK 76 which was followed by BK 38 (42.0%), DPS 47 (41.1%) and IIMRKM 10 (39.4%).

Grouping of kodo millet cultivars for the leaf blight reaction was carried out and data is presented in Table 3. None of the screened cultivars were highly resistant to leaf blight. However, three cultivars viz., KMV 582, IIMR KM 8 and JK 137 were found to be resistant. Six cultivars viz., BK 34, IIMR KM 7, IIMR KM 9, TNAU 86, CKMV 1 and RK 390-25 were recorded susceptible, whereas five cultivars viz., KMV 581, BK 38, IIMR KM 10, DPS 47 and JK-76 were shown highly susceptible reaction exhibiting more than 50% disease severity.

National Screening Nursery of Kodo millet (NSN)

Data presented in table 4 showed that twenty-one cultivars of kodo millet were screened against leaf blight. Significant variation in leaf blight severity ranging from 9.0 to 65.0% with a mean of 35.0% was recorded in the screened cultivars. Lowest incidence was recorded in RPS 868-1. Whereas, highest incidence was noted in susceptible check *i.e.*, JK 76. All the screened cultivars of kodo millet were grouped in different categories of resistance and susceptibility (table 5). None of the screened cultivars were completely free from the disease and one cultivar RPS 868 -1 was found resistant to leaf blight. Seven cultivars including resistant check *i.e.*, RPS 749, RPS 820-1, RPS 795 1, RPS 763 -1, RPS 659 -1, RPS 815-1 and RK 390-25 were found moderately resistant to the disease. Ten cultivars namely BK 7, RPS 939, RPS 719-1, RPS 799 -1, RPS 785 -1, RPS 797 -1, RPS 708 -1, RPS 692 -1, RPS 660 -1, RPS 900 -1 were recorded as susceptible and three cultivars including susceptible check viz., RPS 737, RPS 771 -1 and JK-76 were shown highly susceptible in the reaction to leaf blight.

Table 2: Performance of kodo millet cultivars screened under KIAVT against leaf blight

S. No.	Cultivar	Leaf blight			Reaction
		Severity (%)		Grade	
		Original data	Transformed data		
1	KMV 581	31.3	33.95	6	S
2	KMV 582	4.9	12.88	2	R
3	BK 34	28.1	31.94	5	MR
4	BK 38	42.0	40.38	7	S
5	IIMR KM 7	24.8	29.59	5	MR
6	IIMR KM 8	8.7	16.99	3	R
7	DPS 47	41.1	39.86	7	S
8	IIMR KM 9	28.9	32.45	5	MR
9	IIMR KM 10	39.4	38.88	6	S
10	JK 137	9.0	17.25	3	R
11	TNAU 86	28.4	32.11	5	MR
12	CKMV 1	23.4	28.56	5	MR
13	RK 390-25*	11.5	18.36	4	MR
14	JK-76**	48.8	44.31	7	S
	Mean	26.5	29.82	5	
	CD (5%)		4.832		
	CV (%)		9.6		

* Resistant Check ** Susceptible Check

Table 3: Grouping of kodo millet cultivars screened under KIAVT based on reaction to leaf blight

Reaction	Grade	No. of cultivars	Name of cultivars
Highly resistant	1	0	-
Resistant	2 to 3	3	KMV 582, IIMR KM 8, JK 137
Moderately resistant	4 to 5	6	BK 34, IIMR KM 7, IIMR KM 9, TNAU 86, CKMV 1, RK 390-25
Susceptible	6 to 7	5	KMV 581, BK 38, IIMR KM 10, DPS 47, JK-76
Highly susceptible	8 to 9	0	-

Table 4: Performance of kodo millet cultivars screened under NSN against leaf blight

S. No.	Cultivar	Leaf blight		Grade	Reaction
		Severity (%)			
		Original data	Transformed data		
1	BK 7	36.7	37.24	6	S
2	RPS 939	48.7	44.26	7	S
3	RPS 737	65.0	53.87	8	HS
4	RPS 749	28.1	32.00	5	MR
5	RPS 820-1	13.7	21.12	4	MR
6	RPS 795-1	27.9	31.85	5	MR
7	RPS 719-1	30.1	32.92	6	S
8	RPS 799 -1	40.8	39.67	7	S
9	RPS 785 -1	31.7	34.13	6	S
10	RPS 868 -1	9.0	17.39	3	R
11	RPS 771 -1	58.8	50.32	8	HS
12	RPS 763 -1	26.9	31.17	5	MR
13	RPS 797 -1	40.8	39.71	7	S
14	RPS 659 -1	27.2	30.20	5	MR
15	RPS 708 -1	32.4	34.63	6	S
16	RPS 815-1	25.7	30.46	5	MR
17	RPS 692 -1	41.1	39.87	7	S
18	RPS 660 -1	31.1	33.80	6	S
19	RPS 900 -1	43.5	41.21	7	S
20	RK 390-25(R)	10.1	18.15	4	MR
21	JK-76(S)	65.0	53.98	8	HS
	Mean	35.0	35.62		
	CD (5%)		6.739		
	CV (%)		11.5		

Table 5: Grouping of kodo millet cultivars screened under NSN based on reaction to leaf blight

Reaction	Grade	No. of cultivars	Name of cultivars
Highly resistant	1	0	-
Resistant	2 to 3	1	RPS 868 -1
Moderately resistant	4 to 5	7	RPS 749, RPS 820-1, RPS 795-1, RPS 763 -1, RPS 659 -1, RPS 815-1, RK 390-

Reaction	Grade	No. of cultivars	Name of cultivars
			25
Susceptible	6 to 7	10	BK 7, RPS 939, RPS 719-1, RPS 799 -1, RPS 785 -1, RPS 797 -1, RPS 708 -1, RPS 692 -1, RPS 660 -1, RPS 900 -1
Highly susceptible	8 to 9	3	RPS 737, RPS 771 -1, JK-76

Plant resistance is commonly used and is the most economical and feasible way for the control of leaf blight disease in kodo millet while looking to the status of its growers. In present study, in KIAVT fourteen cultivars of kodo millet and in NSN twenty-one cultivars trials were screened. None of the cultivar was completely resistant in both the trials. However, three cultivars *viz.*, KMV 582, IIMR KM 8, JK 137 in KIAVT and single cultivar RPS 868 -1 in NSN were found resistant to leaf blight. Thirteen cultivars which include resistant check RK 390-25 were moderately resistant and fifteen cultivars showed susceptible reaction. Three cultivars including susceptible check JK 76 were found highly susceptible to leaf blight disease. Previously, 155 kodo millet entries (Singh *et al.*, 1987) and 26 germplasm (Hariprasad *et al.*, 2018) were screened and few sources of resistance were recognized. On contrary, RK 390-25 was reported highly susceptible to leaf blight by Hariprasad *et al.*, 2018. This was moderately resistant to leaf blight in the present study. All the four cultivars showing resistance in the present investigation were also found resistant at Bengaluru. Whereas, three cultivars namely IIMR KM 8, KMV 582 and JK 137 were shown moderately resistant reaction at Nandyal (Andhra Pradesh). Two cultivars *i.e.*, KMV 582 and IIMR KM 8 were found resistant to leaf blight at Mandya (Karnataka). Kodo millet cultivar RK 390-25 was also found moderately resistant at Bengaluru, Mandya and Nandyal (Palanna *et al.*, 2024). These reports confirm the result of present findings.

Conclusion

In conclusion, the cultivars *viz.*, KMV 582, IIMR KM 8, JK 137 in KIAVT and RPS 868 -1 in NSN were found to be resistant against leaf blight of kodo millet incited by *A. tenuissima*.

Conflict of interest: The authors declare that they have no conflict of interest to disclose.

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SEAWEEDS IN AGRICULTURE: BIOFERTILIZERS, BIOSTIMULANTS AND SUSTAINABLE FARMING

B. Deepika* and P. Ganesan

Department of Fish Processing Technology, Fisheries College and Research Institute,
Thoothukudi – 628 008

*Corresponding Email: deepikabaskar143@gmail.com

Abstract

Sustainable agriculture has become a global priority to ensure food security while conserving natural resources and minimizing environmental degradation. Seaweeds, commonly known as marine macroalgae, have emerged as eco-friendly agricultural inputs because of their rich composition of essential nutrients, plant growth regulators, amino acids, vitamins, minerals, polysaccharides, and bioactive compounds. Seaweed-based biofertilizers and biostimulants improve soil fertility, stimulate seed germination, enhance root development, increase nutrient uptake, improve crop yield and quality, and strengthen plant tolerance against abiotic stresses such as drought, salinity, and temperature fluctuations. Unlike synthetic fertilizers, seaweed products promote sustainable farming by improving soil microbial activity, reducing chemical fertilizer dependence, and enhancing environmental health. Their application through seed treatment, foliar spray, soil drenching, and fertigation has shown promising results in cereals, vegetables, fruits, pulses, and plantation crops. With increasing emphasis on organic farming, regenerative agriculture, and climate-smart crop production, seaweed-based products are gaining widespread acceptance among farmers and agripreneurs. This article highlights the role of seaweeds as biofertilizers and biostimulants, their mechanisms of action, agricultural applications, benefits, commercial potential, and future prospects in promoting sustainable agriculture.

Keywords: Seaweeds, Biofertilizers, Biostimulants, Sustainable agriculture, Organic farming, Soil health, Plant growth regulators, Marine bioresources, Crop productivity, Climate-smart agriculture.

Introduction

Agriculture forms the backbone of India's economy, supporting the livelihoods of more than half of the country's population. However, increasing demand for food, declining soil fertility, excessive use of chemical fertilizers and pesticides, climate change, and shrinking natural resources have created major challenges for sustainable crop production. These concerns have encouraged scientists and farmers to explore environmentally friendly alternatives that improve productivity without harming ecosystems.

One such promising solution is the use of seaweeds. Seaweeds are large marine algae naturally found along coastal regions and are classified into green (Chlorophyta), brown (Phaeophyceae), and red (Rhodophyta) groups. For centuries, coastal communities in countries such as Japan, China, Korea, Ireland, and Norway have applied seaweeds directly to agricultural fields to improve soil fertility and crop performance. Today, advances in marine biotechnology have enabled the development of seaweed-based biofertilizers, liquid extracts, biostimulants, and soil conditioners that are widely used in modern agriculture.

Unlike conventional fertilizers that mainly supply nutrients, seaweed products enhance plant growth by stimulating physiological and biochemical processes. They improve nutrient use

efficiency, promote root development, increase resistance to environmental stress, and enhance crop quality. As agriculture moves towards sustainability, seaweed-based products are becoming an important component of integrated nutrient management and climate-resilient farming.

What are Seaweeds?

Seaweeds are multicellular marine algae that grow naturally in oceans, seas, estuaries, and rocky coastal habitats. They perform photosynthesis like terrestrial plants but differ in structure, lacking true roots, stems, and leaves. Depending on the pigments present, seaweeds are grouped into three major categories.

Group	Colour	Common Genera	Agricultural Importance
Green algae	Green	<i>Ulva</i> , <i>Enteromorpha</i>	Soil conditioner, compost, liquid fertilizers
Brown algae	Brown	<i>Sargassum</i> , <i>Turbinaria</i> , <i>Ascophyllum</i> , <i>Laminaria</i>	Rich source of alginates, plant growth promoters, commercial biostimulants
Red algae	Red	<i>Gracilaria</i> , <i>Gelidium</i> , <i>Kappaphycus</i>	Source of agar and carrageenan; improves soil moisture and microbial activity

Among these, brown seaweeds are the most widely used for commercial agricultural products because they contain high concentrations of natural growth-promoting substances such as auxins, cytokinins, gibberellins, betaines, alginates, fucoidans, and polyphenols.

Nutritional and Bioactive Composition of Seaweeds

Seaweeds are often referred to as "marine biofactories" because they contain a wide range of nutrients and biologically active compounds that benefit plant growth.

Major nutrients

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)
- Calcium (Ca)
- Magnesium (Mg)
- Sulphur (S)

Micronutrients

- Iron (Fe)
- Zinc (Zn)
- Copper (Cu)
- Manganese (Mn)
- Boron (B)
- Molybdenum (Mo)

Bioactive compounds

- Auxins
- Cytokinins
- Gibberellins
- Betaines
- Amino acids
- Vitamins

- Alginates
- Laminarin
- Mannitol
- Fucoidan
- Carrageenan
- Agar
- Polyphenols
- Antioxidants

These compounds work synergistically to improve plant metabolism, stimulate enzyme activity, enhance photosynthesis, and increase tolerance to environmental stress.

Seaweeds as Biofertilizers

Biofertilizers are natural products containing living microorganisms or biologically active substances that improve nutrient availability and soil fertility. Seaweed-based biofertilizers differ from chemical fertilizers because they enrich the soil ecosystem while supplying essential nutrients. Seaweed extracts improve the physical, chemical, and biological properties of soil. They increase organic matter content, enhance water-holding capacity, improve soil aeration, and stimulate beneficial microbial populations. Continuous application contributes to healthier soils with improved nutrient cycling.

How Seaweed Biofertilizers Work

Seaweed-based products promote plant growth through several mechanisms:

- Improve soil structure and aggregation.
- Enhance microbial diversity and activity.
- Increase nutrient availability.
- Stimulate root elongation and branching.
- Improve water retention in soil.
- Enhance chlorophyll synthesis.
- Increase photosynthetic efficiency.
- Promote flowering and fruit development.

Unlike synthetic fertilizers, which primarily supply nutrients, seaweed biofertilizers activate natural biological processes that improve nutrient use efficiency and long-term soil health.

Benefits of Seaweed Biofertilizers

Scientific studies have demonstrated several advantages of seaweed application in agriculture:

Improved Seed Germination

Seaweed extracts enhance germination percentage by activating enzymes responsible for seed metabolism and early seedling development.

Enhanced Root Growth

Natural plant hormones present in seaweeds stimulate root elongation, lateral root formation, and root hair development, enabling plants to absorb more water and nutrients.

Increased Nutrient Uptake

Seaweed polysaccharides improve nutrient availability in the rhizosphere and enhance the efficiency of nitrogen, phosphorus, and potassium utilization.

Better Soil Health

Regular application increases organic carbon content, improves soil structure, and promotes beneficial microorganisms such as nitrogen-fixing and phosphate-solubilizing bacteria.

Improved Water-Holding Capacity

Alginates present in brown seaweeds help soils retain moisture, making crops more resilient during dry periods.

Higher Crop Yield

Seaweed-treated crops often produce higher yields due to improved plant vigor, increased flowering, better fruit set, and enhanced nutrient utilization.

Seaweeds as Natural Biostimulants

One of the most remarkable properties of seaweeds is their ability to function as plant biostimulants. According to modern agricultural science, a biostimulant is a substance that enhances plant growth and productivity by improving physiological processes rather than acting solely as a fertilizer. Seaweed biostimulants stimulate plant metabolism through naturally occurring compounds such as auxins, cytokinins, gibberellins, betaines, amino acids, vitamins, and polysaccharides. These compounds promote stronger root systems, improve photosynthesis, enhance nutrient uptake, delay leaf senescence, and increase tolerance to drought, salinity, and heat stress. Unlike chemical growth regulators, seaweed biostimulants are biodegradable, environmentally safe, and compatible with sustainable farming systems.

Mechanisms of Action of Seaweed Biostimulants

Seaweed biostimulants promote plant growth through multiple physiological, biochemical, and molecular mechanisms. Unlike conventional fertilizers that mainly provide nutrients, seaweed extracts activate natural metabolic pathways, enabling plants to utilize nutrients more efficiently and withstand adverse environmental conditions.

1. Enhanced Root Development

Seaweed extracts contain naturally occurring auxins and cytokinins that stimulate root elongation, lateral root formation, and root hair development. A well-developed root system enables plants to absorb greater quantities of water and nutrients, resulting in vigorous growth and improved productivity.

2. Improved Photosynthesis

Seaweed-derived compounds enhance chlorophyll synthesis, increase leaf area, and improve photosynthetic efficiency. Higher photosynthetic activity results in increased carbohydrate production, leading to better vegetative growth, flowering, and fruit development.

3. Better Nutrient Uptake

Polysaccharides such as alginates improve soil structure and facilitate nutrient availability. Seaweed extracts also stimulate microbial activity in the rhizosphere, enhancing the availability and uptake of nitrogen, phosphorus, potassium, and micronutrients.

4. Increased Tolerance to Abiotic Stress

Climate change has increased the frequency of drought, salinity, flooding, and temperature extremes. Seaweed biostimulants help plants tolerate these stresses by:

- Maintaining cellular water balance
- Increasing antioxidant enzyme activity

- Protecting cell membranes
- Enhancing osmotic adjustment through betaines and amino acids
- Reducing oxidative damage caused by reactive oxygen species

5. Improved Flowering and Fruit Set

Natural growth-promoting substances present in seaweeds encourage early flowering, improve pollen viability, reduce flower drop, and enhance fruit setting, resulting in increased yields and better-quality produce.

6. Activation of Plant Defence Mechanisms

Seaweed extracts stimulate the production of defense-related enzymes and compounds that improve resistance against certain diseases and environmental stresses. Compounds such as laminarin and fucoidan are known to induce natural defense responses in plants.

Methods of Application

Seaweed products are available in several formulations, including liquid extracts, soluble powders, granules, and composted materials. The method of application depends on the crop, growth stage, and product formulation.

Foliar Spray

Foliar application is the most widely adopted method because nutrients and bioactive compounds are rapidly absorbed through leaf surfaces.

Benefits:

- Quick absorption
- Improved photosynthesis
- Enhanced flowering
- Better fruit quality
- Rapid stress recovery

Seed Treatment

Seeds are soaked in diluted seaweed extract before sowing to improve germination and seedling vigour.

Advantages:

- Uniform germination
- Strong seedlings
- Better root establishment
- Improved early growth

Soil Application

Seaweed powder, compost, or granules are incorporated into the soil before planting.

This method:

- Improves soil fertility
- Enhances microbial activity
- Increases organic matter
- Improves moisture retention
- Supports long-term soil health

Root Dipping

Seedlings of vegetables, rice, and horticultural crops can be dipped in diluted seaweed extract before transplanting.

Benefits include:

- Reduced transplant shock
- Faster root establishment
- Improved survival rate
- Vigorous early growth

Fertigation

Liquid seaweed extracts can also be applied through drip irrigation systems, ensuring uniform distribution and efficient nutrient utilization while reducing labour requirements.

Benefits in Different Crops

Seaweed-based products have demonstrated positive effects across a wide range of agricultural and horticultural crops.

Cereal Crops

In rice, wheat, and maize, seaweed application has been associated with:

- Improved germination
- Increased tillering
- Higher chlorophyll content
- Enhanced grain filling
- Increased grain yield

Pulse Crops

In legumes such as green gram, black gram, chickpea, and pigeon pea, seaweed extracts improve:

- Nodulation
- Nitrogen fixation
- Pod formation
- Seed weight
- Protein content

Vegetable Crops

Vegetables respond particularly well to seaweed biostimulants.

Benefits include:

- Increased plant height
- Larger leaves
- Better flowering
- Higher fruit set
- Improved colour and taste
- Extended shelf life

Vegetables showing positive responses include tomato, chilli, brinjal, okra, cabbage, cauliflower, cucumber, onion, and leafy greens.

Fruit Crops

Fruit crops such as mango, banana, papaya, grapes, citrus, guava, and pomegranate benefit through:

- Improved flowering
- Reduced fruit drop
- Increased fruit size
- Better sweetness
- Enhanced vitamin content
- Longer storage life

Plantation Crops

Tea, coffee, coconut, arecanut, cocoa, and spices also respond favourably to seaweed applications by exhibiting improved growth, higher productivity, and greater tolerance to drought stress.

Seaweeds in Organic Farming

Organic farming emphasizes the use of natural inputs while minimizing synthetic chemicals. Seaweed-based products perfectly complement organic production systems because they are biodegradable, environmentally friendly, and compatible with organic certification standards.

Seaweed products contribute to organic farming by:

- Reducing dependence on chemical fertilizers
- Enhancing soil biodiversity
- Improving nutrient cycling
- Increasing soil organic matter
- Promoting beneficial microorganisms
- Supporting sustainable crop production

As consumer demand for organically produced food continues to rise, seaweed biostimulants are becoming increasingly important in eco-friendly agriculture.

Role in Climate-Smart Agriculture

Climate change poses serious challenges to agriculture through erratic rainfall, prolonged droughts, floods, and increasing temperatures.

Seaweed biostimulants contribute to climate-smart agriculture by:

- Improving drought tolerance
- Enhancing water-use efficiency
- Reducing salinity stress
- Increasing nutrient-use efficiency
- Improving soil carbon sequestration
- Enhancing resilience against extreme weather events

These benefits help farmers maintain productivity while adapting to changing climatic conditions.

Commercial Seaweed-Based Agricultural Products

Several companies now manufacture commercial seaweed formulations in liquid, powder, and granular forms. Most products are prepared using brown seaweeds such as *Ascophyllum nodosum*, *Sargassum*, and *Laminaria*.

Common products include:

- Seaweed liquid fertilizers
- Seaweed plant growth promoters
- Seaweed biostimulants
- Organic nutrient formulations

- Seaweed compost enhancers
- Seed treatment formulations

Farmers should always use registered products and follow the manufacturer's recommended dosage for optimum results.

Business Opportunities for Agripreneur

The expanding demand for eco-friendly agricultural inputs offers exciting opportunities for rural youth and start-ups.

Potential enterprises include:

- Seaweed cultivation
- Seaweed extract manufacturing
- Liquid biofertilizer production
- Organic input retailing
- Nursery and horticulture supplies
- Crop advisory services
- Online marketing of biofertilizers
- Custom spraying services

With appropriate training and quality assurance, seaweed-based businesses can become profitable and environmentally sustainable ventures.

Challenges

Despite their immense potential, widespread adoption of seaweed products faces several challenges:

- Limited awareness among farmers
- Seasonal availability of raw seaweed
- Lack of processing infrastructure
- High transportation costs
- Variability in product quality
- Need for standardization
- Limited extension activities
- Inadequate market linkages

Addressing these constraints requires collaboration among research institutions, government agencies, industry, and farmers.

Future Prospects

The future of seaweed-based agriculture is highly promising. Increasing emphasis on sustainable farming, regenerative agriculture, organic food production, and climate resilience is expected to drive greater adoption of seaweed biostimulants worldwide. Advances in marine biotechnology are facilitating the development of highly concentrated seaweed extracts enriched with specific bioactive compounds. Precision agriculture, nanotechnology, microbial consortia, and digital farming are likely to enhance the efficiency of seaweed-based products further. India possesses abundant coastal resources and a rapidly growing seaweed cultivation sector, creating enormous opportunities for farmers, entrepreneurs, and researchers. Integrating seaweed farming with agriculture can strengthen the Blue Economy while supporting national goals of environmental sustainability and food security.

Conclusion

Seaweeds have emerged as valuable natural resources that bridge marine and agricultural ecosystems. Their rich composition of nutrients, plant growth regulators, polysaccharides, and bioactive compounds makes them highly effective biofertilizers and biostimulants for improving crop productivity and soil health. Regular application enhances seed germination, root growth, nutrient uptake, stress tolerance, crop quality, and overall farm profitability while reducing dependence on synthetic fertilizers. Beyond crop production, seaweed-based products offer significant opportunities for entrepreneurship, rural employment, and sustainable industrial development. As awareness increases and technologies continue to evolve, seaweed-derived agricultural inputs are expected to play an increasingly important role in organic farming, climate-smart agriculture, and regenerative farming systems. Harnessing the immense potential of India's marine bioresources will contribute to resilient agricultural production, environmental conservation, and the long-term sustainability of the nation's food systems.

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SOIL HEALTH MANAGEMENT: THE KEY TO SUSTAINABLE AGRICULTURE

Botha Prashanthi

Assistant Professor, School of Agricultural Sciences,
Malla Reddy University
Corresponding Email: drprashanthibotha@gmail.com

Introduction

Soil is far more than the loose material beneath our feet it is a living system that links the rock beneath, the air above, and the water that moves through it. Within this thin, dynamic layer, physical, chemical, and biological processes work together to support plant growth, cycle nutrients, filter water, and sustain the countless organisms that make agriculture possible. As the world's population continues to grow, the pressure on farmland to produce more food, without degrading the resource base that makes production possible, has never been greater. Meeting this challenge depends on one central idea: soil health. Understanding and actively managing it is now recognized as the foundation of sustainable agriculture.

Keywords: Soil, Health, Management, Food

What Soil Health Really Means

Soil health is generally described as the continued capacity of soil to function as a living system sustaining biological productivity, maintaining environmental quality, and supporting plant, animal, and human health. It is often used interchangeably with the term "soil quality," though the two carry slightly different emphases: soil health reflects the soil's condition at a given time, much like a person's health, while soil quality reflects its capacity over a longer period, more like an overall quality of life. Whatever term is used, the underlying message is the same soil is not an inert growing medium but an ecosystem that must be nurtured to keep functioning well.

The Physical Foundation

A soil's physical condition determines how well water infiltrates, how easily roots penetrate, and how much air reaches the organisms living below the surface. Healthy soils have good tilth a crumbly, well-aggregated structure rich in organic matter along with sufficient depth, balanced pore space, and resistance to compaction. Aggregation is central to this picture: soil particles bound together by organic residues, microbial secretions, and fungal threads form macro- and micro-pores that regulate the movement of water and air. When soils lose organic matter through excessive tillage or are compacted by heavy machinery, aggregates break down, infiltration slows, runoff and erosion increase, and roots struggle to grow. Conversely, minimizing disturbance and returning organic residues to the field builds structure, improves water storage, and buffers crops against both drought and waterlogging.

The Chemical Balance

Chemically, soil health depends on maintaining an appropriate pH, adequate but not excessive nutrient levels, and a strong capacity to hold and exchange those nutrients. Most crops thrive in a slightly acidic to neutral pH range, since this window maximizes the availability of nitrogen, phosphorus, potassium, and micronutrients while limiting the solubility of toxic elements such as

aluminum. Soil organic carbon underlies much of this chemical fertility: it improves cation exchange capacity, stabilizes aggregates, and serves as the primary reservoir from which nutrients are released as microbes decompose organic matter. Excess fertilizer inputs, on the other hand, can unbalance this system, leading to nutrient runoff, groundwater contamination, and even increased vulnerability of crops to pests. Careful, soil-test-based nutrient management supplying what the crop needs rather than what is simply convenient keeps this chemical balance intact over time.

The Living Component

Perhaps the most remarkable aspect of soil health is biological. A single teaspoon of fertile soil can contain hundreds of millions of bacteria, along with fungi, protozoa, nematodes, earthworms, and other organisms that together form an intricate food web. Bacteria and fungi decompose organic residues and release nutrients in forms plants can absorb; mycorrhizal fungi extend a plant's effective root system in exchange for carbon; nitrogen-fixing bacteria convert atmospheric nitrogen into forms usable by crops; and earthworms physically engineer soil structure by burrowing, mixing, and creating stable channels for water and roots. This biodiversity does more than cycle nutrients it also suppresses soil-borne pathogens through competition and antagonism, reducing the need for chemical intervention. Because these organisms respond quickly to changes in management, biological indicators such as microbial biomass, soil respiration, and enzyme activity are increasingly used as early-warning signals of soil degradation or recovery.

Managing for Healthy Soil

These three dimensions physical, chemical, and biological do not operate in isolation; they are deeply interconnected, and management decisions that affect one will inevitably influence the others. This is the logic behind conservation agriculture, an approach built on three linked principles: minimal mechanical soil disturbance, permanent organic soil cover through residues or cover crops, and diversified crop rotations. Reducing tillage protects aggregate structure and preserves organic matter; keeping the soil covered shields it from raindrop impact, moderates temperature, and conserves moisture; and rotating diverse crops interrupts pest and disease cycles while feeding a wider range of soil organisms. Field studies across many regions and crops have linked these practices to higher aggregate stability, greater water-holding capacity, increased organic carbon storage, improved nutrient cycling, and larger, more diverse microbial and earthworm populations compared with conventional, intensively tilled systems. The benefits, however, typically build gradually — often taking several years to fully appear — which means soil health management requires a long-term commitment rather than a single-season fix. Organic amendments such as compost and manure, along with reduced reliance on synthetic inputs, further reinforce this recovery by feeding both the chemical and biological components of the soil system simultaneously.

Because soil health cannot be measured directly, scientists rely on a minimum set of representative indicators spanning all three categories, summarized below.

Category	Key Indicator	Why It Matters
Biological	Microbial biomass	Source and reservoir of carbon and nutrients
Biological	Soil respiration	Reflects microbial activity and organic matter turnover
Biological	Nitrogen mineralization	Indicates the soil's capacity to supply nitrogen to crops
Chemical	Organic carbon	Supports structure, fertility, and water-holding capacity

Category	Key Indicator	Why It Matters
Chemical	pH	Governs nutrient availability
Chemical	Cation exchange capacity	Reflects the soil's ability to retain and supply nutrients
Physical	Aggregation	Indicator of structure and resistance to erosion
Physical	Infiltration	Governs runoff and erosion risk
Physical	Water-holding capacity	Ensures moisture availability for plant growth

(Adapted from a minimum data set commonly used for soil health assessment.)

A Long-Term Investment

Ultimately, healthy soil is resilient soil able to rebound after a poor harvest year, a compaction event, or a period of drought, and to keep functioning without a costly rescue in the form of extra fertilizer, irrigation, or pesticide. Achieving this resilience requires farmers, scientists, and policymakers to think of soil not as a static input but as a living partner in food production. Simple, proven practices reducing unnecessary tillage, keeping the ground covered, diversifying rotations, and returning organic matter to the field can, over time, restore the physical structure, chemical balance, and biological richness that together define a healthy, productive soil. In an era of growing food demand and mounting environmental pressure, soil health management is not an optional refinement; it is the key to keeping agriculture sustainable for generations to come.

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SOIL METAL ACCUMULATION IN LEAFY GREEN VEGETABLES MORE THAN FRUITING VEGETABLES

Suryansh Pandey^{1*}, Udham Singh² and Sanjana Singh³

¹Department of Soil Science, College of Agriculture,
Banda University of Agriculture and Technology, Banda, U.P. - 210001

²Department of Vegetable Science, College of Horticulture,
Banda University of Agriculture and Technology, Banda, U.P. -210001

³Department of Soil Science, College of Agriculture,
Banda University of Agriculture and Technology, Banda, U.P. - 210001

*Corresponding Email: psuryansh81@gmail.com

Abstract

The wastewater irrigation is the result of heavy metal contaminated agricultural soils which increases the concern due to food safety issues and potential health risks. This causes in the accumulation of heavy and trace metals in vegetables. Consumption of vegetables containing (heavy/trace) metals is one of the main ways in which these elements enter the human body, once entered heavy metals are deposited in bone and fat tissues, overlapping noble mineral and causes in disease formation. The present study aimed to study and investigate the concentration of different metal in agricultural soil and vegetables grown on those soils and to evaluate the possible health risks to human body through food chain transfer. Based on metal accumulation in edible parts and whole plants, root vegetables namely radish and carrot registered lower accumulation of almost all heavy metals except zinc (Zn) in radish root. However, leafy vegetables namely spinach, amaranths, mustard and fenugreek recorded higher accumulation of both essential and non-essential heavy metals, except cadmium (Cd) and nickel (Ni) which showed less accumulation in fenugreek. Contamination levels in soils and vegetables with metals were measured and transfer factors (TF) from soil to vegetables and its health risk were calculated. Results showed that concentration of Si, Ba, K, Ca, Mg Fe, Sc, V, Cr, Cu, Zn, As, Mn, Co, Ni, Se, Sr, Mo, and Cd in soil is higher than the world average value and Al, Ti and Pb is lower than the World Average value whereas concentration of toxic elements like As, Co, Cu, Mn, Pb, Se, Ni, V and Zn in vegetable samples are below the world average value. The Hazard Quotient (HQ) for Fe, Cu, Co, Cr, V, Ni, Pb, Mn, Zn and Cd were calculated which showed a decreasing order of Cd>Mn>Zn>Pb>Cu>Fe>Ni>V=Co>Cr. Highest HQ value found for Cd (2.543) which is above the safe value.

Introduction

The accumulation of heavy metals and metalloids in agricultural soil is of increasing concern now a day. Potentially harmful metal in soil may come from the bedrock and anthropogenic sources like solid or liquid waste deposits, agricultural inputs and fallout of industrial and urban emissions (Wilson



and Pyatt 2007). Excessive accumulation in agricultural soils results in soil contamination and has consequences for food quality and safety.

Food is the major intake source of toxic metals by human beings. Among food system, vegetables are the most exposed food to environmental pollution due to aerial burden. Vegetables take up heavy metals and accumulate them in their edible and non-edible parts at quantities high enough to cause clinical problems to both animals and human beings. Excessive content of metals beyond Maximum Permissible level (MPL) leads to number of nervous, cardiovascular, renal, neurological impairment as well as bone diseases and several other health disorders.

In the low concentrations, many metals are essential to life (Kashif *et al.*, 2009). Trace quantities of certain heavy elements such as Co, Cu, Mn and Zn are essential micronutrients for plants (Somers, 1974). However, excessive accumulation of trace elements in agricultural soils through wastewater irrigation may not only result in soil contamination, but it also affects food quality and safety (Muchuweti *et al.*, 2006; Sharma *et al.*, 2007). Some trace elements are essential in plant nutrition, but plants growing in the nearby zone of industrial areas accumulate increased concentration of heavy metals, serving in many cases as bio monitors of pollution loads. The accumulation of soil metals are higher in leafy vegetables (like spinach, mustard greens, and lettuce) than fruity vegetables (like tomato, potato, peppers, and brinjals) are due to the soil-root interaction, water transport mechanics, and internal biological barriers.

Leafy vegetables slightly do higher evaporation than fruity vegetables. They have large, wide surface area and high density of stomata. This creates massive upward suction force. Heavy metals dissolved in soil pore water (like Cd, Zn, and Pb) are taken upward through water highways and deposited directly into the edible parts of leaves. Whereas, Fruits have a thick, waxy outer cuticles and very few stomata opening, which results in little transpiration. Because the water suction towards the fruit weak, water-bound metal ions are naturally diverted away from fruit and sent to the plant's structural leaves.

Methods to Measure

The soil testing methods are very important before planting, which majorly provides all the contained elements of soil. The modern techniques made it easy to evaluate any such type of elements which are held inside the soil. These all methods can be conducted through KVKs and several institutes.

Portable X-Ray Fluorescence (pXRF)

In a practical field setting, a handheld pXRF instrument is used to measure the metal ions held inside the given field. It helps to convert this sub-atomic physics into digital quantitative data through a synchronized hardware loop. When operator pulls the device trigger, an internal X-ray tube (containing Rhodium, Tungsten, or gold anode) is energized. It accelerates the electron across a high voltage gap to generate a continuous spectrum of X-ray, which exit through a protective window of instrument directly to the targeted soil matrix. The X-ray penetrate the top few millimetres of



soil sample. They interact with soil matrix, causing heavy metals (Pb, Zn, Cu, etc.) present within the soil particle and scatter secondary characteristics X-ray back towards the nose of the Gun. The X-ray which comes backward to the gun is measured with the help of Multi-Channel Analyzer (MCA) which categorizes this incoming voltage pulses based on their height (energy level). The position of peaks on energy spectrum identifies which metal ions are present in the soil.

Transfer Factor

Metal concentration in the extracts of soils and plants were calculated on the basis of dry weight. The plant transfer factor (TF) was calculated as follows:

$$TF = C_{\text{plant}} / C_{\text{soil}}$$

Where C_{plant} and C_{soil} represent the toxic metal concentration in extract of plants and soil on dry weight basis

Calculation of health risk index of metal contamination of vegetable

Risk to human health by the intake of metal-contaminated vegetables was characterized using a hazard Quotient (HQ). HQ is the ratio between exposure and the reference oral dose (RfD). If the ratio is lower than one (1), there will be no obvious risk. An estimate of the potential hazard of metal to human health (HQ) through consumption of vegetables is determined by the following equation

$$HQ = (\text{Div}) \times (C_{\text{metal}}) / RfD \times Bo$$

Where (Div) is the daily intake of vegetables (kg/day), (C_{metal}) is the concentration of metal in the vegetable (mg/kg), RfD is the oral reference dose for the metal (mg/kg of body weight/day) and Bo is the human body weight (kg). Although the HQ-based risk assessment method does not provide a quantitative estimate for the probability of an exposed population experiencing a reverse health effect, it indeed provides an indication of health risk level due to exposure to pollutants.

Laboratory Testing of Vegetable Tissues

For testing the metal concentration in vegetable, some laboratory experiments are conducted which can provide the value and types of accumulated metal ions, it requires the Destructive Preparation like:

- Vegetables (especially leafy greens) must be washed with tap water, followed by 0.1% HCL bath, and finished with multiple rinses of Milli-Q deionized water. This step removes all external soil particles and atmospheric dust.
- Samples are dried thoroughly in a hot-air oven until they reach constant weight. Removing 100% of the water weight allows results to be expressed in mg/kg of dry weight.
- The dried plant tissues are ground using mortar and pestle or contamination free micro mill to form a fine, uniform powder
- The powder (usually around 0.1g to 0.5g) is placed into a vessel with Nitric Acid (HNO_3) and Hydrogen Peroxide (H_2O_2). The solution is cooked in a microwave digestion system or a hot-block heater at temperature 95-180°C. This burns away the organic carbon plant matter, leaving behind a perfectly clear, liquid acid solution containing only isolated metal ions.

Once the digested vegetable liquid is prepared, it is injected into high-precision lab instruments to get exact quantitative data:

Instrument	Sensitivity (Detection Limit)	Metals
AAS (Atomic Absorption spectroscopy)	Parts per million (ppm)	Zn and Pb
ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy)	Parts per billion (ppb)	Simultaneous testing of major nutrients and moderate heavy metals across large batches.
ICP-MS (Inductively Coupled Plasma Mass Spectrometry)	Parts per trillion (ppt)	Cd, As, and Hg

Conclusion and Future Prospects

From the soil management prospective, the accumulation of heavy metals in foliar tissue highlights how to manage contaminated agricultural soil. Because leafy green vegetables possess high nutrient extraction which results in drawing mobile divalent cations from soil matrix, they easily exploit soil with low Cation Exchange Capacity CEC or acidic pH profile. To safely cultivate these high-risk crops, soil remediation must be applied for total elemental removal. Applying amendments like biochar, lime, or phosphates compound alter the soils surface charge and raises its pH. While fruiting vegetables benefit from the filters present in fruits that isolate them from poor soil conditions, leafy green safety is entirely dependent on the quality like pH, EC, CEC, etc. of the soil matrix. Metal contamination in Soil is receiving increasing attention all over the world. Principally there are two major pathways for human exposure to soil contamination: soil-plant-human (foodchain pathway) and soil-human (incidental soil ingestion). Concentration of different elements in vegetables depends upon the relative level of exposure of plants to the contaminated soil as well as the deposition of toxic elements in the polluted air by sedimentation.

The daily intake of metals (Fe, Cu, Mn, Zn, Co, Cr, V, Ni, Pb, Cd) for human with a average body weight 70 kg have been found that intake of toxic metals from vegetables is not high and within the suggestive values. The calculated Hazard Quotient (HQ) for the above elements except Mn, Zn and Cd is found below 1 which indicates safe with no risk to human health. Higher HQ value for Mn and Zn may not pose risk to human health because these are the essential elements for human. Further in most of the vegetables concentration of Mn is found below the detection level except bean.

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SPEED BREEDING IN VEGETABLES: ACCELERATING GENETIC GAINS FOR THE FUTURE

**Shashiprabha Verma¹, S. K. Acharya¹,
Varun Dwivedi² and Ojaswitha Rao¹**

¹Department of Vegetable Science, College of Horticulture,
Sardarkrushinagar Dantiwada Agriculture University, Jagudan,
Mahesana - 384460 Gujarat, India.

²Department of Vegetable Science, College of Horticulture,
Sardar Vallabhbhai Patel University of Agriculture and Technology,
Meerut - 250110, Uttar Pradesh, India.

*Corresponding Email: singh.shashi9780@gmail.com

Abstract

Vegetable crops are important sources of vitamins, minerals, dietary fibre and antioxidants and play a crucial role in ensuring food and nutritional security. However, challenges such as climate change, water scarcity, emerging pests and diseases and shrinking cultivable land have increased the need for rapid development of improved vegetable varieties. Speed breeding is an innovative plant breeding approach that accelerates crop improvement by manipulating environmental rapid conditions such as light, temperature, humidity, nutrients and irrigation to shorten the plant life cycle. It allows the production of multiple generations year, significantly reducing the time required to develop new vegetable varieties. The technique has been successfully applied in crops such as tomato, lettuce, pepper, spinach, carrot and cucumber leading to the rapid development of varieties with improved yield, nutritional quality, disease resistance and stress tolerance breeding programme. Despite some limitations, the integration of speed breeding with modern breeding technologies offers a promising and sustainable solution for enhancing vegetable crop improvement and ensuring future food and nutritional security.

Introduction

Vegetable crops play a pivotal role in global food and nutritional security by providing essential vitamins, minerals, dietary fibre and antioxidants required for a healthy diet. The demand for vegetables is increasing due to rapid population growth, urbanization and greater awareness of the health among the masses. However, vegetable production is facing several challenges, including climate change, water scarcity, emerging pest diseases and the continuous reduction in arable land. These challenges necessitate the rapid development of improved vegetable varieties with higher yield potential, superior quality and enhanced tolerance to biotic and abiotic stresses in over changing climate. Plant breeding has traditionally been the primary method used to improve crop performance. Although effective, conventional breeding is often slow and may require several years or even decades to release a new variety. The technology has emerged as a valuable tool for vegetable crop improvement and sustainable agricultural development.

Concept of Speed Breeding

Speed breeding is a process that accelerates the life cycle of plants by providing ideal growing conditions. According to Watson *et al.* (2018), speed breeding is a process that helps to develop new crop varieties more quickly and easily. The major purpose is to decrease the time period

between subsequent generations, allowing breeders to produce more generations per year than under normal field conditions. The strategy focuses on environmental manipulation rather than genetic modification alone. Plants are exposed to extended light time, controlled temperatures and suitable growth conditions to induce faster growth and earlier flowering. As a result, plants complete their life cycle more quickly, enabling rapid selection and breeding. Speed breeding was initially developed for cereal crops but has now been successfully applied to several vegetable crops, including peppers, amaranth, tomato, lettuce, spinach, carrot and cucumber.

Speed Breeding components



Artificial Lighting: Modern LED lighting systems are widely used in speed breeding facilities. LEDs provide specific wavelengths required for photosynthesis and plant development. Compared with traditional lighting systems, LEDs consume less energy, produce less heat and allow precise control over light quality and intensity. This makes them ideal for year-round crop production. (Turner & Smith, 2023).

Temperature: Temperature affects seed germination, vegetative growth, flowering and fruit development. Speed breeding systems maintain optimum temperatures for most of crops grow best within specific temperature ranges, usually 12–30 °C for germination and 25–30 °C for growth and reproduction. According to Went (1953), warmer daytime and cooler nighttime temperatures promote healthy plant development and aid in stress recovery throughout the plant life cycle. Consistent temperature conditions reduce stress and promote rapid growth. Day and night temperatures are carefully adjusted according to crop requirements to maximize productivity.

Optimized Growing Environment: In addition to light and temperature, environmental factors such as relative humidity, along with nutrient and water supply are carefully regulated throughout the plant life cycle (Hickey *et al.*, 2018). These optimized conditions provide an ideal environment for plant growth and contribute to reducing generation time.

Photoperiod: Light is one of the most important factors for plant growth. In speed breeding, plants receive almost continuous light (20–22 hours per day), generally 22 hours of light and 2 hours of darkness (Hickey *et al.*, 2018). This increases photosynthesis and energy production, helping in plants growth and flower emerge quickly.

Importance of Speed Breeding in Vegetable Crops

Vegetable crops are an important source of vitamins, minerals, fibre and antioxidants. People all over the world are eating more vegetables because they are becoming more aware of healthy diets. Speed breeding offers several benefits for vegetable improvement: rapid development of new varieties, faster incorporation of desirable traits, increased breeding efficiency, reduced breeding costs over time, enhanced adaptability to climate change, improved food and nutritional security. The ability to produce multiple generations annually enables breeders to respond quickly to market demands and emerging agricultural challenges.

Application of Speed Breeding in Vegetable Crops

According to Demers *et al.*, (1998), increasing the duration of light exposure can reduce the time required to complete a generation in crops like tomato, pepper and amaranth thereby accelerating breeding progress.

Tomato (*Solanum lycopersicum*) is most suitable in speed breeding research because it has a relatively short growth cycle and responds well to controlled environmental conditions. The use of extended photoperiods and optimized temperature regimes significantly accelerates flowering and fruit development. Speed breeding of tomato was evaluated in a plant factory using cultivars Zuanhongmeili and Xiaokeai (Hu *et al.*, 2025). Under a 12 h photoperiod, light intensities of 300–400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ accelerated development, enabling flower bud emergence at ~25 DAS and germinable seed harvest at 60–63 DAS. Using 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, photoperiod optimization showed that a 20 h photoperiod further promoted growth and reproductive development. Under these conditions, seeds were harvested at 72–76 DAS. Overall, optimized light regimes can enable up to six tomato generations per year in controlled environments, supporting rapid breeding (Hu *et al.*, 2025).

Lettuce (*Lactuca sativa*) has a naturally short life cycle, making it highly suitable for speed breeding programs. Breeders have successfully improved leaf quality, drought tolerance, nutrient content and resistance to bolting. These advancements lead to increased output and improved environmental adaptation (Marquez & Kumar, 2023).

Spinach (*Spinacia oleracea*) is a leafy vegetable that exhibits a strong positive response to prolonged photoperiods. Because the crop is highly sensitive to day length, manipulating light duration can be an effective strategy for promoting flowering and seed production. LED-based speed breeding with extended photoperiods (13–19 h) significantly enhanced spinach vegetative growth, with a 19-h photoperiod producing the highest stem length, root length ($\approx 30\%$ increase), leaf area and plant weight while reducing necrosis and chlorosis (Ibrahim *et al.*, 2025).

Carrot (*Daucus carota*) Speed breeding has accelerated the development of carrot varieties with improved disease resistance and nutritional quality. Special emphasis has been placed on increasing beta-carotene content, which is an important precursor of vitamin-A enhancement in nutritional value contributes to better human health and nutrition (Raza & Choi, 2022).

Cucumber (*Cucumis sativus*) breeding programs have benefited significantly from speed breeding techniques. Researchers have developed varieties with improved fruit quality, higher yield potential, enhanced pest resistance and greater tolerance to environmental stresses. Rapid generation advancement enables quick identification of superior breeding lines (Marquez & Kumar, 2023).

Advantages of Speed Breeding

1. Multiple generations can be produced in a single year.
2. It accelerates the development of improved crop varieties.
3. Increased genetic gain per unit time.
4. It improves the efficient use of breeding resources and facilities.
5. Enhanced response to climate-related challenges.
6. Reduced dependence on seasonal conditions.
7. Improved efficiency of modern breeding technologies.

8. Faster incorporation of disease resistance genes.
9. Greater flexibility in breeding programs.
10. It supports the goals of sustainable agricultural development.

Challenges of Speed Breeding

High Initial Investment: Setting up controlled-environment facilities requires expensive equipment such as artificial lighting systems, temperature control units and specialized infrastructure.

High Energy Consumption: Continuous lighting and environmental control systems consume large amounts of electricity, increasing operational costs.

Crop-Specific Responses: Different crops and varieties respond differently to speed breeding conditions, so protocols need to be standardized for each species/crop.

Risk of Reduced Genetic Diversity: Focusing on a limited number of desirable traits may narrow the genetic base, making crops more vulnerable to future stresses.

Future Prospects

Speed breeding is likely to become increasingly significant in future vegetable crop improvement programs. Ongoing developments in controlled environment agriculture, energy-efficient lighting and automation are making this approach more practical, affordable and widely applicable. When combined speed breeding with modern molecular breeding tools such as marker-assisted selection, genomic selection and genome editing, it can greatly accelerate the development of improved cultivars. It also has strong potential in climate resilience research by allowing faster assessment of plant responses to various environmental stresses. Moreover, this technique can aid in producing vegetables with enhanced nutritional value, thereby supporting better human health and nutrition outcomes.

Conclusion

Speed breeding is an innovative and promising technique used to speed up vegetable crop improvement. It works by controlling environmental conditions such as light duration, temperature and light intensity, which promotes faster plant growth and allows several generations to be produced within a single year. In vegetable breeding programs, the use of speed breeding can greatly shorten the time needed to develop new varieties with desirable traits such as higher yield, better quality and improved tolerance to environmental stresses. While there are some limitations to its use, continuous technological progress and its combination with modern breeding approaches are likely to improve its effectiveness and wider application. Overall, speed breeding is a valuable approach for addressing the increasing demand for vegetables and will be minimized future agricultural challenges.

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SUSTAINABLE FISHERIES RESOURCE MANAGEMENT**Varsha, Bhargav¹ Adhikari² and Diri Khalo³**

College of Fisheries, G. B. Pant University of Agriculture and Technology (GBPUAT),
Pantnagar Uttarakhand – 263145

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Sustainable fisheries resource management is essential for conserving aquatic ecosystems and ensuring the long-term availability of fisheries resources. It helps maintain biodiversity while supporting the livelihoods and food security of millions of people. Unsustainable fishing practices and overfishing have caused habitat destruction, reduced fish populations, and disturbed ecological balance. Bycatch and trophic cascades have further contributed to biodiversity loss and disruptions in aquatic food webs. Maximum Sustainable Yield (MSY) is a key principle used to maintain fish stocks at sustainable levels. The use of selective fishing gear reduces the capture of non-target species and promotes responsible fishing practices. Closed seasons and closed areas allow fish populations to reproduce and recover naturally. Effective fisheries management includes quota systems, community-based approaches, and monitoring, control and surveillance (MCS) mechanisms. Climate change and illegal, unreported, and unregulated (IUU) fishing continue to threaten fisheries resources. Therefore, strong international cooperation and strategic management pathways are necessary for the conservation and sustainable use of fisheries resources.

Keywords: Aquatic ecosystems, overfishing, habitat destruction, Maximum Sustainable Yield (MSY), fisheries management.

Introduction

Sustainable fishing is a responsible way of fishing that works with the natural ability of aquatic ecosystems to regenerate. It helps protect fish stocks for future generations by making sure that fishing activities do not exceed ecological limits. This approach combines environmental protection with socioeconomic equity and encourages responsible governance and fair access to resources. As the demand for seafood increases worldwide, sustainable fishing practices are important for preventing resource depletion and conserving freshwater and marine biodiversity. Sustainable fishing also supports the welfare of inland and coastal fishing communities by ensuring food security and providing long-term income. Through innovation, education, and effective management, sustainable fishing helps create healthier ecosystems and more resilient livelihoods.

Definition and Importance

The term “sustainable fishing” refers to the practice of catching fish in a way that maintains the long-term health and productivity of the target species as well as the surrounding freshwater or marine ecosystems. This concept balances ecological integrity with the socioeconomic needs of present and future generations. It emphasizes biodiversity conservation, science-based management, responsible fishing practices, and minimal environmental impact. The importance of sustainable fishing is very significant. Fish and other aquatic species are an important source of protein for billions of people worldwide, especially in developing countries. Therefore, maintaining the availability of these resources is essential for food security, livelihoods, and economic

development. In addition, sustainable fishing practices help aquatic ecosystems become more resilient to pollution, habitat degradation, and climate change.

Principles of Sustainable Fishing

Sustainable fishing is based on a set of guidelines that aim to balance ecological health, economic feasibility, and social responsibility. These principles are founded on scientific knowledge, precautionary management, and long-term environmental stewardship. When these principles are effectively implemented, fish populations can be maintained at productive levels, environmental impacts can be reduced, and the well-being of communities dependent on aquatic resources can be supported.

Maximum Sustainable Yield (MSY)

Maximum Sustainable Yield (MSY) is an important concept in fisheries management from both ecological and economic perspectives (Al Arif, 2017). It refers to the maximum amount of fish that can be harvested from a fish stock over a long period without reducing the stock's ability to recover. MSY is used as a benchmark to determine safe harvest levels and to prevent overexploitation of fish resources. The implementation of MSY requires detailed stock assessments, including information on fish population size, growth rates, recruitment, and natural mortality. However, environmental variability and data limitations can make accurate estimation difficult. Therefore, many modern fisheries management frameworks adopt a precautionary approach by setting harvest limits below the estimated MSY to account for natural fluctuations and management uncertainties.

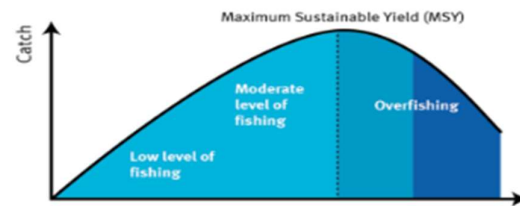


Fig.1 Maximum Sustainable Yield (MSY)

Selective Gear and Methods

The use of selective fishing gear and methods is important for reducing bycatch and minimizing damage to aquatic habitats. Selective gears are designed to catch specific species or sizes of fish while allowing non-target organisms to escape unharmed. Examples include:

- Gill nets with appropriate mesh sizes to avoid catching juvenile fish.
- Circle hooks in longline fisheries to reduce turtle and seabird bycatch.
- Turtle excluder devices (TEDs) in trawl nets to allow sea turtles to escape.
- Pole-and-line fishing, which reduces bycatch compared with large-scale purse seine fishing.

The adoption of eco-friendly fishing gear helps conserve biodiversity, improves the quality of the catch, and supports long-term sustainability.

Seasonal and Area Closures

Seasonal and area closures are management tools used to protect vulnerable species, critical habitats, and important life stages of fish populations. These closures restrict fishing activities in specific areas or during certain periods of time. Depending on the management objectives, the closures may be temporary, seasonal, or permanent. They help protect breeding grounds, nursery areas, and feeding habitats, allowing fish populations to reproduce and recover naturally.

- a) **Seasonal Closures:** Seasonal closures are usually imposed during spawning periods so that fish populations can breed without disturbance. For example, on the East Coast, the uniform fishing ban in the Indian EEZ outside territorial waters does not apply to traditional

non-motorized fishing units (Ministry of Fisheries, Animal Husbandry and Dairying, New Delhi, 2025).

- b) **Area Closures:** Area closures help protect breeding sites, nursery grounds, and ecological hotspots from harmful fishing practices.
- c) **Marine Protected Areas (MPAs) and Fishery Management Zones (FMZs):** These areas are used to conserve marine ecosystems and improve fishery productivity through spillover effects.

Fisheries Management Strategies

Effective fisheries management is essential for maintaining the health of aquatic ecosystems, supporting the livelihoods of fishing communities, and ensuring the long-term sustainability of fish stocks. Each fishery has its own biological and socioeconomic characteristics; therefore, management plans should be flexible, inclusive, science-based, and adapted to local conditions. Sustainable fisheries management commonly uses several important strategies to achieve these objectives.

Quotas and Licensing Systems

Catch quotas and licensing systems are important tools for controlling fishing activities and preventing overexploitation. Quotas set the maximum allowable catch for a particular species within a specific time period and geographic area, based on scientific assessments of stock productivity and abundance. Licensing systems regulate access to fisheries by limiting the number of fishing vessels or individuals allowed to fish and may specify fishing seasons, gear types, and operating zones. Together, quotas and licenses help maintain fish stocks at sustainable levels by controlling fishing effort and aligning it with natural limits. Their effectiveness depends on proper enforcement, transparent allocation processes, and reliable data collection. Some countries also use individual transferable quotas (ITQs) to encourage responsible fishing, but these systems must be carefully designed to avoid fairness concerns and resource privatization.

Community-Based and Co-Management Approaches

Community-based fisheries management (CBFM) and co-management approaches recognize the important role of local stakeholders in the sustainable management of fisheries. Under these systems, fishing communities and government authorities share responsibility for managing fishery resources, often with support from non-governmental organizations and academic institutions. CBFM uses local customs, cultural norms, and community institutions to regulate access, enforce rules, and monitor compliance. Co-management further strengthens this approach by integrating scientific knowledge, legal frameworks, and state support. These methods are particularly effective in inland and small-scale fisheries, where centralized management may be difficult. Their benefits include improved resource stewardship, reduced conflicts, higher compliance with regulations, and the adoption of locally appropriate conservation measures.

Examples: The community fish sanctuaries in South and Southeast Asia, self-regulated seasonal bans and customary marine tenure systems in Pacific Island nations.

Monitoring, Control and Surveillance (MCS)

Monitoring, Control and Surveillance (MCS) are essential components of fisheries management because they ensure that regulations are followed and illegal activities are detected and prevented. MCS includes the following elements:

- a) **Monitoring:** Collecting data on fishing effort, catches, landings, and compliance with regulations.
- b) **Control:** Establishing legal frameworks that define acceptable behavior, including laws, regulations, and licensing requirements.
- c) **Surveillance:** Monitoring and enforcing compliance through patrols, inspections, and technologies such as satellite tracking, electronic logbooks, and Vessel Monitoring Systems (VMS).

Table 1. Key Fisheries Management Strategies and Their Functions

Management strategy	Main Function
Catch quotas	Maintain fish harvest within sustainable limits.
Licensing systems	Regulate access to fisheries and control fishing effort.
Selective fishing gear	Reduce bycatch and protect non-target species.
Area closures	Conserve breeding sites, nursery grounds, and ecological hotspots.
Community-based management	Involve local stakeholders in fisheries management and decision-making.
Monitoring, Control and Surveillance (MCS)	Ensure compliance with regulations and detect illegal fishing activities.

Ecological Impacts of Unsustainable Fishing

The effects of unsustainable fishing methods on aquatic ecosystems, biodiversity and ecological balance are extensive. These effects include habitat destruction, food web disturbance and long-term ecosystem instability in addition to the immediate reduction of fish supplies. Designing and putting into practice sustainable fishing methods requires an understanding of these ecological effects.

Habitat Destruction

Some fishing methods can seriously damage aquatic habitats. Bottom trawling, for example, can destroy coral reefs, uproot seagrass beds, and disturb benthic ecosystems. These habitats are important breeding, nesting, and feeding grounds for many aquatic species, so their loss reduces biodiversity and ecosystem productivity. In freshwater ecosystems, habitat modification such as damming and dredging, along with overharvesting, can fragment fish populations and reduce spawning success. Destructive practices such as cyanide and dynamite fishing cause immediate physical damage and degrade biologically rich habitats. As a result, habitat destruction affects both target fish populations and the overall health of aquatic ecosystems.

Bycatch and Biodiversity Loss

Bycatch refers to the accidental capture of non-target species during fishing operations. It often includes marine mammals, sea turtles, seabirds, juvenile fish, endangered species, and non-commercial invertebrates. Many of these organisms are discarded dead or dying, leading to wasteful mortality and declines in vulnerable species populations. High levels of bycatch reduce biodiversity by decreasing genetic diversity and increasing the risk of extinction for some species. This loss of biodiversity weakens ecosystem resilience and disrupts important ecological processes such as nutrient cycling, predation control, and habitat maintenance. As a result, aquatic ecosystems become less stable and less productive.

Trophic Cascades and Ecosystem Imbalance

Overfishing often reduces populations of top predators such as sharks and large predatory fish. The removal of these predators can trigger trophic cascades, where changes at one trophic level affect many other species in the food web. For example, a decline in large predatory fish may increase mid-level predators, reduce herbivore populations, and contribute to algae overgrowth and coral reef decline. This process, known as “fishing down the food web” (Ainley & Pauly, 2014), can shift ecosystems toward smaller, faster-reproducing species at lower trophic levels. Such changes reduce ecological integrity and biodiversity, making aquatic ecosystems less stable and more vulnerable to invasive species, diseases, pollution, and climate change.

Challenges and Future Directions**Climate Change and Ocean Acidification**

Climate change and ocean acidification pose serious challenges to fisheries by affecting water temperatures, ocean currents, and breeding cycles. Warming waters can change the distribution of fish species, while ocean acidification affects shell-forming organisms and may reduce their survival. These changes can make existing fisheries management zones less effective. In inland fisheries, especially in tropical regions such as India, unpredictable rainfall and temperature fluctuations can affect productivity and spawning patterns. To address these challenges, important adaptive measures include:

- Dynamic management models
- Climate-resilient species selection in aquaculture
- Ecosystem-based adaptation strategies

These approaches can help improve the resilience of fisheries and support sustainable resource management under changing environmental conditions.

Illegal, Unreported and Unregulated (IUU) Fishing

Illegal, unreported, and unregulated (IUU) fishing is a major challenge to sustainable fisheries management. It distorts markets, weakens conservation efforts, and often has a greater impact on developing countries. IUU fishing includes activities such as fishing without permits, underreporting catches, and using prohibited gear or fishing methods.

To reduce and prevent IUU fishing, the following measures are important:

- Strong Monitoring, Control and Surveillance (MCS) systems
- International cooperation and data sharing
- Trade restrictions on illegally sourced fish
- Community-based monitoring and enforcement

These measures can help improve compliance, strengthen enforcement, and support the sustainable management of fisheries resources.

Policy and Governance

The governance, policy frameworks and regulatory enforcement must be firmly established for sustainable fisheries management. Efficient governance guarantees that regulations are grounded on empirical data, applied equitably and flexible enough to accommodate ecological and socioeconomic realities.

National Regulations and Compliance

In order to control fisheries in their inland waters and exclusive economic zones (EEZs), national governments are primarily responsible for creating rules and regulations. These rules could consist of:

- a) Catch limits and licensing schemes
- b) Minimum mesh sizes and gear restrictions
- c) Prohibitions against fishing in specific areas and seasons
- d) Size restrictions and endangered species protection

In India, fisheries management is regulated under the Indian Fisheries Act, 1897, state-level legislation, and Marine Fishing Regulation Acts (MFRAs) for coastal fisheries (Shyam et al., 2010). Compliance is enforced by fisheries departments, coast guards, and local institutions. However, weak institutional capacity, limited monitoring infrastructure, and low awareness among fishers can hinder effective implementation. Therefore, strengthening legal frameworks and promoting participatory governance are essential for improving compliance and sustainability.

Role of International Bodies

International organizations play an important role in developing global fisheries policies, providing scientific guidance, and managing transboundary fish stocks. The Food and Agriculture Organization (FAO) supports responsible fisheries through global guidelines, data collection, and capacity-building programs. Regional Fisheries Management Organizations (RFMOs), such as the Indian Ocean Tuna Commission (IOTC) and the Western and Central Pacific Fisheries Commission (WCPFC), help conserve and manage fish stocks that move across national boundaries. They also assist in resolving fishing conflicts, sharing scientific information, and promoting standardized management measures. Their role is becoming increasingly important as climate change affects the distribution of fish stocks.

Conclusion

Sustainable fishing is important not only for environmental conservation but also for economic well-being. It requires a balance between protecting aquatic biodiversity and supporting the livelihoods of millions of people who depend on fisheries. Although challenges such as illegal, unreported, and unregulated (IUU) fishing and climate change continue to affect fisheries, resilience can be strengthened through technological advancements, community-based governance, and science-based policies. By learning from past successes and failures, adopting inclusive management strategies, and promoting international cooperation, sustainable fisheries management can become a practical reality that conserves aquatic resources for present and future generations.

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SUSTAINABLE SHRIMP FARMING: THE SCIENCE OF POND WASTE CONTROL

G. Dhivagar, L. Vinoth Kumar*, E. K. Devipriya, M. Dhanu Pradeep, R. Gayathri and S. T. Dhivya Bharathi

^{1,3,4,5,6}B.F.Sc Scholar, Department of Fish Processing Technology, TNJFU- Dr.MGR. Fisheries College and Research Institute, Ponneri, Thiruvallur District, Tamil Nadu 601204

²Assistant professor, Department of Fish Processing Technology, TNJFU - Fisheries College and Research Institute, Thoothukudi-628 008, Tamil Nadu.

*Corresponding Email: vinothkumar@tnfu.ac.in

Abstract

Shrimp aquaculture has grown rapidly, but waste accumulation in ponds remains a major challenge. A large portion of feed is not converted into shrimp biomass and instead settles as organic waste, leading to oxygen depletion and the release of toxic compounds like ammonia and hydrogen sulfide. The shrimp pond “toilet system” offers a practical solution by using water circulation and a sloped pond design to concentrate waste in a central collection area for easy removal. This prevents harmful decomposition and improves water quality. Structural additions such as HDPE covers further enhance efficiency and shrimp safety.

Overall, this system converts waste management into an active process, reducing environmental stress and improving farm productivity.

Keywords: Shrimp aquaculture, Pond toilet system, Waste management, Organic sludge, Water quality, Hydrodynamics, Aeration, Ammonia toxicity, Hydrogen sulfide, Sustainable aquaculture

Introduction

Shrimp farming is booming. It feeds millions of people and supports livelihoods worldwide. But behind every successful shrimp pond lies an uncomfortable truth, these systems generate a huge amount of waste. And if that waste isn't managed properly, the entire system can collapse. In modern aquaculture, farmers push ponds to produce more by adding large amounts of feed. But shrimp don't convert all that feed into growth. A significant portion sinks to the bottom as uneaten pellets, feces, and organic debris. Over time, this waste builds up, turning the pond floor into a toxic zone. As it decomposes, it releases harmful substances like ammonia and hydrogen sulfide, chemicals that stress shrimp, slow their growth, and open the door to deadly diseases. Think of a shrimp pond like a closed room. If no one cleans it, waste accumulates, and eventually, nothing can survive comfortably. The same thing happens underwater. Without proper waste control, even a well-managed farm can quickly face poor water quality and sudden crop failure. To tackle this problem, farmers have developed smarter ways to “clean” their ponds. One of the most practical solutions is the concept of a shrimp toilet a simple system designed to collect and remove waste from the pond bottom before it becomes dangerous. Instead of letting sludge spread everywhere, it is concentrated in one place and removed regularly.

What Is a Pond Toilet System

Think of it as a centralized waste collection system built directly into the pond. Instead of letting waste spread randomly across the pond bottom, farmers design the pond so that all the sludge

naturally moves toward a central collection point. From there, it can be removed efficiently before it starts causing problems.

Working Principle of the Shrimp Toilet

The working principle begins with water movement inside the pond. Shrimp ponds are usually equipped with paddle wheel aerators that create a continuous circular flow of water. This movement is not random, it acts like a natural conveyor system. Uneaten feed, fecal matter, and organic debris are gradually pushed toward the center of the pond. This happens because the outer edges experience higher water velocity, while the center remains relatively calm. As a result, heavier particles settle in this low-energy central zone. The shrimp toilet system takes advantage of this natural behavior. At the center of the pond, a specially designed pit or depression is constructed, typically occupying about 5–7% of the total pond area. The bottom of the pond is sloped gently (around 25–30 degrees) toward this central pit. Because of this slope, gravity works along with water currents to guide the accumulated waste directly into the pit.

Once the waste reaches the pit, it becomes highly concentrated. Instead of being spread throughout the pond, the sludge collects in a small, controlled area. This is the critical point where management becomes efficient. The collected waste is then removed periodically, usually once a week, using a siphon system or a pump. In some cases, gravity-based drainage systems are used to discharge the sludge without mechanical effort. An important improvement to this system is the use of an HDPE parabola cover placed above the central pit. This dome-shaped structure enhances the working principle in two ways. First, it reduces disturbance from water currents, allowing more particles to settle into the pit. Second, it increases suction efficiency during waste removal by directing the flow of water and sludge toward the drain point. At the same time, it prevents shrimp from accidentally entering the pit during suction.

The science behind this system is straightforward but crucial. When organic waste accumulates in the pond bottom, it decomposes under low oxygen conditions, producing harmful substances like ammonia and hydrogen sulphide. These compounds are toxic to shrimp and weaken their immune system, making them more vulnerable to diseases. By removing the waste early, before decomposition intensifies, the shrimp toilet interrupts this harmful process. In essence, the shrimp toilet works by combining hydrodynamics (water movement), gravity (sloped design), and controlled extraction (siphoning or drainage) into a single system. It transforms the pond from a passive environment into a managed system where waste is actively directed, collected, and removed.

What makes this approach effective is not complexity, but timing and precision. Waste is not allowed to stay long enough to become dangerous. Instead, it is continuously guided to a central point and taken out of the system. This simple mechanism significantly improves water quality, reduces stress on shrimp, and supports healthier and more productive aquaculture systems.

Conclusion

Shrimp toilet systems turn waste management from a problem into a controlled process. By directing, concentrating, and removing sludge early, they prevent toxic buildup before it harms the crop. This improves water quality, shrimp health, and overall farm productivity. In simple terms, cleaner ponds mean stronger shrimp and more reliable harvests.

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ENGINEERING NATURE'S WORKFORCE USING SYNTHETIC MICROBIAL CONSORTIA FOR ECO-FRIENDLY CROP PROTECTION

D. Shanmuga Priya* and C. Jeyalakshmi

Department of Plant Pathology,
Pandit Jawaharlal Nehru College of Agriculture and Research Institute,
Karaikal - 609603, U.T. of Puducherry, India.

***Corresponding Email:** dshanmugapriya95@gmail.com

Introduction

Plants do not grow alone, they live in close association with billions of microorganisms that inhabit the soil, roots, leaves, and surrounding environment. These microscopic partners play vital roles in nutrient cycling, disease suppression, stress tolerance, and overall plant health. For decades, agriculture has relied on single microbial inoculants such as beneficial bacteria or fungi to improve crop productivity. Although these individual microbes can provide significant benefits, they often fail to perform consistently under diverse field conditions because no single microorganism can carry out all the functions required for healthy crop growth. To overcome this limitation, researchers have turned their attention to synthetic microbial consortia (SynComs), carefully designed communities of compatible microorganisms that work together to perform multiple beneficial functions. By combining microbes with complementary traits, such as nutrient solubilization, plant growth promotion, pathogen suppression, and stress mitigation, SynComs can mimic the cooperative interactions found in natural plant microbiomes while offering greater reliability and functionality than single-strain inoculants. The growing interest in SynComs reflects a broader shift toward sustainable agriculture, where biological solutions are increasingly being explored to reduce dependence on chemical fertilizers and pesticides. Advances in microbiome research, genomics, and synthetic biology have made it possible to identify beneficial microorganisms, understand their interactions, and assemble tailored microbial communities for specific crops and environments. As a result, synthetic microbial consortia are emerging as a promising next-generation technology for improving crop health, enhancing productivity, and building resilient agricultural systems capable of meeting future food security challenges.

Designing Synthetic Microbial Consortia

Developing an effective synthetic microbial consortium begins with the careful selection of microorganisms that can work together rather than compete with one another. Each microbial member is chosen for its unique functional traits, such as nutrient solubilization, nitrogen fixation, plant growth promotion, pathogen suppression, or stress tolerance. Before combining them, researchers evaluate their compatibility and interactions to ensure that the selected microorganisms complement each other and remain stable under different environmental conditions. The ultimate goal is to create a balanced microbial community that delivers multiple benefits to the host plant.

Synthetic microbial consortia are primarily designed using two complementary strategies: the top-down and bottom-up approaches. The top-down approach begins with a naturally existing microbial community, such as the rhizosphere microbiome, where high-throughput sequencing, metagenomics, and ecological network analyses are employed to identify microorganisms

associated with desirable plant traits. The complex community is then systematically simplified by selecting key microbial members that contribute to functions such as disease suppression, nutrient acquisition, or stress tolerance. This strategy preserves naturally evolved microbial interactions and provides insights into the ecological mechanisms governing community stability and functionality. In contrast, the bottom-up approach involves the rational assembly of a consortium from individually characterized microbial strains with well-defined functional attributes. Each microorganism is selected based on specific traits, including plant growth promotion, nutrient solubilization, antagonism against pathogens, or abiotic stress mitigation, followed by compatibility testing to ensure cooperative interactions and stable coexistence. This approach offers greater control over community composition, enables mechanistic studies of microbial interactions, and facilitates the development of reproducible microbial formulations. Increasingly, researchers are integrating both approaches to design robust, predictable, and functionally efficient synthetic microbial consortia tailored for sustainable agricultural systems.

How Synthetic Microbial Consortia Benefit Agriculture

Plants exist in close association with diverse microbial communities that profoundly influence their growth, health, and resilience. Synthetic microbial consortia (SynComs) are designed to harness these beneficial interactions by combining microorganisms with complementary functional traits. Unlike single-strain bioinoculants, SynComs perform multiple tasks simultaneously, enabling a more holistic approach to crop management. Through cooperative interactions, the microbial members establish a stable and functional community around plant roots, enhancing nutrient availability, improving plant vigor, and protecting crops from biotic and abiotic stresses.

One of the primary benefits of SynComs is their ability to improve nutrient acquisition. Different microorganisms contribute distinct functions, such as biological nitrogen fixation, phosphate and zinc solubilization, potassium mobilization, and iron acquisition through siderophore production. Together, these activities increase nutrient availability in the rhizosphere, promote root development, and enhance nutrient uptake efficiency, ultimately leading to improved plant growth and higher yields while reducing dependence on chemical fertilizers. Synthetic microbial consortia also play a crucial role in managing plant diseases through multiple complementary mechanisms. Beneficial microorganisms suppress pathogens by producing antimicrobial compounds, hydrolytic enzymes, and volatile organic compounds, while also competing for nutrients and ecological niches. In addition, many SynCom members stimulate the plant's innate immune system by inducing systemic resistance, enabling crops to respond more effectively to pathogen attacks. Because these mechanisms operate simultaneously, SynComs often provide broader and more durable disease protection than individual microbial strains.

Beyond nutrient management and disease suppression, SynComs enhance plant tolerance to environmental stresses such as drought, salinity, heat, and heavy metal toxicity. Certain microorganisms produce phytohormones, osmoprotectants, exopolysaccharides, and ACC deaminase, which help plants maintain physiological balance under adverse conditions. At the same time, microbial activities improve soil structure, stimulate beneficial microbial diversity, and support long-term soil fertility. Collectively, these functions contribute to resilient cropping systems that require fewer chemical inputs and are better equipped to withstand changing climatic conditions. The multifunctional nature of synthetic microbial consortia makes them a promising tool for sustainable agriculture. By integrating nutrient cycling, plant growth promotion, disease management, and stress mitigation into a single biological system, SynComs represent a

next-generation approach to enhancing crop productivity while minimizing environmental impacts. As research continues to improve the design and stability of these engineered microbial communities, their adoption is expected to play a significant role in the transition toward climate-smart and environmentally sustainable farming practices.

Applications of Synthetic Microbial Consortia in Sustainable Crop Production

Synthetic microbial consortia are emerging as a versatile biological tool with wide-ranging applications in sustainable crop production. By integrating microorganisms with complementary functional traits, SynComs provide multiple ecosystem services that support crop productivity while reducing the environmental footprint of agriculture. Their ability to perform diverse functions simultaneously makes them suitable for developing next-generation bioinputs that can replace or supplement conventional agrochemicals. One of the most promising applications of SynComs is in the development of multifunctional biofertilizers. Unlike conventional microbial inoculants containing a single strain, SynCom-based biofertilizers combine microorganisms capable of nitrogen fixation, phosphorus and micronutrient solubilization, potassium mobilization, and phytohormone production. This integrated approach improves nutrient use efficiency, enhances root architecture, and promotes healthy plant growth, thereby reducing the dependence on synthetic fertilizers.

SynComs are also being explored as advanced biocontrol agents for the management of plant diseases. Carefully selected microbial partners suppress pathogens through complementary mechanisms, including antibiotic production, secretion of hydrolytic enzymes, competition for nutrients and ecological niches, and activation of induced systemic resistance in plants. Their combined activity often provides broader-spectrum and more consistent disease suppression than single microbial strains, making them valuable components of integrated disease management strategies. Another important application lies in improving crop resilience to abiotic stresses such as drought, salinity, heat, and nutrient-deficient soils. Microbial consortia help plants cope with these stresses by enhancing water and nutrient uptake, regulating plant hormone balance, producing stress-protective metabolites, and improving root–soil interactions. These benefits contribute to stable crop performance under changing climatic conditions and support the development of climate-resilient agricultural systems. In recent years, SynComs have also gained attention in rhizosphere engineering and precision agriculture. Advances in microbiome research, genomics, artificial intelligence, and systems biology are enabling the design of crop-specific microbial communities tailored to different soils, climates, and cropping systems. Such customized microbial formulations have the potential to improve resource-use efficiency, restore soil health, and increase productivity while minimizing chemical inputs. As these technologies continue to evolve, synthetic microbial consortia are expected to become a cornerstone of regenerative and sustainable agriculture, supporting global efforts toward food security and environmental conservation.

Challenges and Future Prospects

Despite their immense potential, the successful implementation of synthetic microbial consortia (SynComs) in agriculture faces several scientific and practical challenges. Designing stable and functionally robust microbial communities remains difficult due to the complexity of microbial interactions and their sensitivity to varying soil types, climatic conditions, and agricultural practices. Ensuring long-term survival, root colonization, and consistent performance under field conditions, as well as developing compatible formulations with adequate shelf life, are critical

hurdles for large-scale commercialization. Furthermore, regulatory frameworks, biosafety assessments, and standardized evaluation protocols for multi-strain microbial products are still evolving in many countries. Future research should focus on integrating advances in microbiome science, multi-omics technologies, systems biology, artificial intelligence, and machine learning to predict microbial interactions and design highly efficient, crop-specific SynComs. Coupled with innovative delivery systems and precision agriculture, these next-generation microbial communities have the potential to reduce reliance on agrochemicals, enhance climate resilience, improve soil health, and play a transformative role in achieving sustainable and environmentally responsible crop production.

Conclusion

Synthetic microbial consortia represent a paradigm shift in sustainable agriculture by moving beyond single-strain inoculants toward functionally integrated microbial communities capable of delivering multiple agronomic benefits. Through cooperative interactions, these engineered microbial assemblies enhance nutrient acquisition, promote plant growth, suppress diseases, improve tolerance to environmental stresses, and contribute to long-term soil health. Although challenges related to community stability, field performance, formulation, and regulatory approval remain, rapid advances in microbiome research, synthetic biology, and computational tools are accelerating the development of robust and predictable SynComs. As our understanding of microbial ecology continues to expand, synthetic microbial consortia are poised to become an integral component of next-generation agricultural technologies, offering environmentally friendly solutions that support resilient crop production, reduce dependence on chemical inputs, and contribute to global food security in the face of climate change.

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THE PLANT PATHOBIOME: BEYOND THE ONE PATHOGEN-ONE DISEASE PARADIGM

Sakshi Pandey, Nazia Manzar and Abhijeet Shankar Kashyap*

ICAR-National Bureau of Agriculturally Important Microorganisms,
275103, Uttar Pradesh, India

*Corresponding Email: Abhijeet4497@gmail.com

Abstract

Traditional pathology has long stuck to the “one pathogen-one disease” paradigm; however, recent research suggests this model has oversimplified the complex interactions that lead pathogenicity. This review explores the transition of the traditional concept towards the pathobiome concept, which defines pathogenesis as a multidimensional interaction among a pathogen, the host, the resident microbial community of host, and surrounding environment. Advancement in meta-omics technology like metagenomics, metatranscriptomics, and metabolomics enables the researchers to understand the resident microbes that act as “friends and foes” in this complex interaction. Antagonistic interaction between the resident microbes suppresses the disease through the mechanism like nutrient competition, antibiosis, and physical exclusion. Conversely, pathobionts promote the infection by cross-feeding nutrients, suppressing the host’s immune system and producing synergistic phytotoxins. Developing studies on the wheat leaf blight complex illustrates how co-infection by *Bipolaris*, *Alternaria*, and *Curvularia* species significantly increases disease severity compared to single-pathogen model. Similarly, Grapevine Esca, Acute Oak Decline, and Pine Wilt Disease are considered as stress-mediated holobiont disorders driven by polymicrobial assemblages and multi-kingdom interaction. Future perspectives in this field, include artificial intelligence and deep learning models for understanding and detecting early, high accuracy detection of complex symptomatic patterns. Moreover, research is moving ahead toward the pathobiome engineering, which enables the design of synthetic microbial consortia to enhance holobiont resilience. Ultimately this paradigm will shift the focus from the narrow perspective of the origin of disease towards the maintenance and restoration of host health.

Introduction

Recent advancements in technologies and plant pathology brought a major shift from the traditional “One Pathogen-One Disease” model to more comprehensive concept of “Patho biome” (Antony-Babu, 2025 and Kashyap, 2026). For over a decade, disease researches were guided by Koch’s postulates and Hill’s postulates, which emphasize isolated microbes and their specific virulence factors.

However, new studies (Lv, 2023) show that pathogenicity is rarely caused by single pathogenic agent, instead, it is a result of complex, multi-dimensional interactions among the pathogen, the host resident microbial community, and the surrounding environment. In the center of this new perspective, the host is accepted as a holobiont – a complex assemblage of microorganisms and their associated microbes (Gramaje, 2026) (Hu, 2025) (Kashyap, 2026). This new ecological view has transformed the new classic view of “disease triangle” (host, pathogen, environment) into a “disease diamond”, which includes the microbiome as the fourth critical determinant of health.

Some frameworks further expand this view into a disease pyramid, adding time as the dimension to capture the shifting dynamics of these biotic and abiotic factors (Leveau, 2024) (Lv, 2023) (Mannaa & Seo, 2021). This evolution is largely driven by meta-omics technologies- including metagenomics, metatranscriptomics and metabolomics -which enable the researchers to understand the diversity and functional activities of unculturable microbial communities which were unraveled (Vayssier-Taussat, Shifting the paradigm from pathogens to pathobiome: new concepts in the light of meta-omics., 2014) (Wright, 2017).

By revealing how resident microbes function as “friends and foes,” the pathogenicity can be suppressed through competition or by facilitating infection via nutrient gross feeding (Vayssier-Taussat, Shifting the paradigm from pathogens to pathobiome: new concepts in the light of meta-omics., 2014). This includes pathobiome engineering to develop disease-suppressive microbial consortia and the integration of artificial intelligence to accurately detect the complex symptom patterns.

Paradigm Shift: From Single Pathogen to Multidimensional Pathogenesis

For over a year, the study of infectious disease was dominated by Koch’s and Hill’s postulates (Antony-Babu, 2025) (Gramaje, 2026) (Hu, 2025). However, recent research demonstrated that pathogenesis is a complex, multi-dimensional interaction of microbial communities (Gramaje, 2026) (Lv, 2023) (Leveau, 2024). Pathogenesis is now considered as pathobiome disorder where the pathogenic agent will interact with the wider biotic environment, including the host and its surrounding microbiota (Mannaa & Seo, 2021) (Ogier, 2020).

Theoretical Framework: The Disease Diamond and Pyramid

Traditional pathology explains infection by disease triangle, which defines the interplay of on only a host, a pathogen, and the environment. To accommodate the critical role of the microbiome, this model has evolved into four dimensional “Disease Diamond” or “Disease Tetragon” which recognizes the resident microbiota as an essential determinant of pathogenicity in the host (Lv, 2023). Some framework further expands this dimension into disease pyramid by including time, which represents the shifting dynamics of overall abiotic and biotic factors over the course of infection (Leveau, 2024).

The Holobiont and it’s Associated Microbes

In this pathobiome concept, the host is considered as the holobiont, which considers the microbiome and other associated microbes as single functional unit (Vayssier-Taussat, 2014). Resident microbes within the holobiont are categorized on the basis of their role: **soterobionts** support in healthy growth and provide defense, while **pathobionts** are commensal members that may become virulent under specific triggers. In plants these communities are divided into niches like rhizosphere and phyllosphere, each possessing a unique composition of strains (Hu, 2025). A recent study on hygroscopic bacteria shows that pathogens can recruit stable bacterial consortia, such as *Pseudomonas species*, to enhance their own fitness and pathogenicity (Antony-Babu, 2025).

Unravelling the Pathobiome through Meta-omics

Meta-omics technologies serve as a toolkit for unravelling these complex relationships by providing high-resolution data on the diversity, activity, and chemical interactions between the microbial communities (Antony-Babu, 2025). Metagenomics allows the researchers to investigate the biodiversity of unculturable microbes, which are present in the pathobiome, while

metatranscriptomics reveals which microbes are active and which virulence genes are being expressed in the plant. Furthermore, metabolomics tracks the chemical release by plants, such as phytotoxins, in their defense against the pathogens (Vayssier-Taussat, 2014). The emerging epigenomics branch suggests that hosts can store memories of past stress through DNA methylation, which may predispose them to future disease outbreaks.

Biotic Interaction: Allies and Opponents

Within the pathobiome, microbes are in continuous physical and chemical interaction which may either suppress or facilitate the disease. They may show two types of interaction. One is the antagonism, in which competition between the microbes suppresses the disease through nutrient competition, by the production of antibiotics or hyperparasitism. For example, the yeast *Moesziomyces bullatus* secretes the enzymes that inhibit the white rust infection in *Arabidopsis* (Eitzen K, 2021). And another is one facilitation, in which helper microbes promote infection via nutrient gross feeding, such as phyllosphere yeasts providing essential thiamine (Vitamin B) to auxotrophic pathogen. (Eitzen K, 2021) Pathogens may also hijack resident microbes to suppress host immunity, creating a more permissive environment for secondary infection.

External Trigger

The external environment is an intrinsic destabilizing force, which influences holobiont's physiology and alters the resident microbiota to the pathobiome state, leading to opportunistic pathogen proliferation (Lv, 2023) (Gramaje, 2026). Primary natural triggers for disease epidemics are weather events, like severe drought or high humidity, and these erode a host's innate immunity, especially jasmonic- acid- regulated resistance, and alter chemical niches to favor pathogenic taxa (Leveau, 2024) (Lv, 2023). Anthropogenic pressures like pollutants (e.g. ozone, microplastics) or intensive use of agrochemicals can destroy phyllospheric diversity and induce "vacuum effect" this allows non- native potentially virulence microbes to colonize the host (Vayssier-Taussat, 2014) (Wright, 2017). In addition, specific environmental factors like pH and phosphorus level are the determinants of microbial community assembly. Extreme environmental conditions can even paradoxically shift parasitic relationship into mutualistic associations, which are crucial to host survival and thermal tolerance.

Future Perspective

The future of pathology is in holistic transition to the pathobiome and holobiont frameworks, beyond the "one pathogen- one disease" paradigm. Major advancement includes the integration of multi-omics integration with AI diagnostics to identify predictive markers in asymptomatic hosts. Management will focus on pathobiome engineering, designing artificial consortia to increase the durability of holobionts. The breeding program will move towards the selection for holobionts stability with a focus on wood biochemistry and microbiome recruitment. Ultimately, the focus of this field is shifting towards maintaining health as an emergent property of complex biotic, environmental, and temporal interactions.

Conclusion

The Pathobiome paradigm marks a fundamental shift from the "One Pathogen-One Disease" model towards a system-based understanding of the holobiont. By integrating AI and meta-omics, researchers can now figure out how complex microbial networks facilitate or suppress disease through their functional interaction. This evolution in the field of plant pathology transforms the concept of disease triangle into a multidimensional disease pyramid or diamond, which includes

the microbiome, environment and time as critical determinants. Future sustainable pathogen management will depend on pathobiome engineering to boost resilience against global environmental changes.

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BATHUA: A TRADITIONAL WINTER GREEN FOR NUTRITION, HEALTH AND SUSTAINABLE FARMING**Karakambadi Vaishnavi^{1*}, Syed Sadarunnisa² and Sangaraju Reddy Veera Nagaveni³**

¹Ph.D. Scholar, Department of Vegetable Science,
Dr. Y.S.R. Horticultural University, College of Horticulture, Anantharajupeta,
Andhra Pradesh, India

²Professor, Department of Vegetable Science,
Dr. Y.S.R. Horticultural University, College of Horticulture, Pulivendula,
Andhra Pradesh, India

³Ph.D. Scholar, Department of Vegetable Science,
College of Agriculture, JNKVV

*Corresponding Email: vaishnavikarakambadi1998@gmail.com

Introduction

A plant growing unnoticed along field bunds, in wheat and mustard fields and on marginal lands may sometimes be more valuable than many vegetables deliberately cultivated with intensive inputs. Bathua (*Chenopodium album* L.) is one such example known as lamb's quarters, common goosefoot or fat hen in English, Bathua has traditionally occupied an important place in winter diets, particularly in northern India. However, despite its nutritional richness, adaptability and multiple uses, it is still commonly regarded as a weed rather than as a valuable vegetable crop. Bathua represents the hidden potential of traditional and underutilized vegetables. It is inexpensive, locally adapted and nutritionally dense. Its tender leaves and shoots are consumed as cooked greens and are also incorporated into paratha, roti, puri, raita and other traditional preparations. The crop can also be dried and stored for off-season use, while its green biomass has value as animal feed. The combination of low cultivation cost, high nutritional quality and multiple uses makes bathua particularly relevant at a time when agriculture is simultaneously facing the challenges of micronutrient malnutrition, climate variability and rising production costs. It is a good source of dietary fibre, vitamins A and C, folic acid and riboflavin, along with important minerals such as iron, calcium and phosphorus (Trivedi and Singh, 2018).

From an unwanted weed to a valuable vegetable

The plant is generally an erect herb with considerable variability in plant height, pigmentation and leaf shape. The stem may be green, reddish or purplish, while the leaves vary from oval and rhomboid to triangular or lanceolate forms. Flowers occur in clusters forming spike-like inflorescences, and the plant produces small, dark seeds. This natural variability provides useful opportunities for selection and genetic improvement. The transformation of bathua from a naturally occurring weed into a cultivated vegetable has already begun. Improved multi-cut cultivars with large leaves, attractive colour, delayed bolting, enhanced nutritional quality and high yield demonstrate that this traditional green has considerable commercial potential.

A natural storehouse of nutrients

The greatest strength of bathua lies in its nutritional density. Its leaves contain protein, dietary fibre, minerals, carotenoids and vitamin C. Different studies have reported variation in nutrient

concentration depending on genotype, plant age, environment and analytical method, but the overall evidence consistently identifies bathua as a nutrient-dense leafy vegetable. A representative composition per 100 g edible portion includes about 3.7 g protein, 0.4 g fat, 4.2 mg iron, 1,740 µg carotene, 35 mg vitamin C and 150 mg calcium. Beyond commonly measured nutrients, bathua also contains a useful spectrum of amino acids. The plant is also rich in bioactive compounds, including flavonoids, polyphenols and other secondary metabolites. These compounds have attracted scientific attention because of their antioxidant activity. Another important consideration is the presence of antinutritional compounds such as oxalates and phytates, as occurs in several leafy vegetables. Appropriate processing is useful because blanching and cooking can reduce oxalic acid, while blanching also helps reduce phytic acid. Therefore, suitable cooking not only improves palatability but can also improve the dietary suitability of bathua Poonia *et al.*, (2015).

Improved Varieties: The foundation for commercial cultivation

The availability of improved cultivars has created new opportunities for bringing bathua from field margins to organized vegetable production. Important cultivars include Pusa Bathua-1, Pusa Green, Kashi Bathua-2 and Kashi Bathua-4.

Pusa Bathua-1 is a multi-cut type characterized by large, dark green leaves and reddish-green plant pigmentation. Tender leaves can be harvested from about 45 days, and the cultivar has an average green leaf yield of approximately 30 t/ha. It has also been reported to possess higher vitamin C and beta-carotene content than locally marketed bathua.

Pusa Green is another multi-cut cultivar with smooth, attractive dark green leaves and luxuriant plant growth. It has a reported leaf yield of about 36.8 t/ha and is characterized by high carotenoid and iron content. Its late-bolting nature is an important advantage because premature flowering reduces the marketable leafy period.

Kashi Bathua-2 produces about 36.7 t/ha green leaf yield and can be harvested repeatedly from around 40 days after sowing up to approximately 120 days at regular intervals. It has also been reported to possess higher phenolic content and antioxidant activity than wild bathua.

Kashi Bathua-4, with purplish-green foliage and pink pigmentation, has a reported green leaf yield of about 40.7 t/ha. Its attractive pigmentation, nutritional attributes and high yield make it an interesting option for diversified leafy vegetable production.

These cultivars clearly demonstrate that bathua need not remain an unmanaged winter weed. Through varietal selection and scientific crop management, it can become a high-yielding and market-oriented leafy vegetable Yadav *et al.*, (2020).

Production Technology

Bathua is essentially a cool-season leafy vegetable. It is fairly tolerant to frost, whereas high temperatures encourage early flowering and shorten the period of vegetative leaf production. It can be grown in different soil types, although sandy loam and loam soils are generally preferred. The crop also possesses a degree of tolerance to saline-sodic conditions.

Sowing and crop establishment

The crop may be established either through direct sowing or transplanting. In the northern plains, October to December is a suitable sowing window depending on local climatic conditions. Because the seed is very small, shallow sowing is essential. For direct sowing, about 1.5-2.0 kg seed per

hectare is required. Seeds can be mixed with fine sand for uniform distribution. For transplanted crops, nursery-raised seedlings of around 30-35 days are used. Row spacing of around 30 cm and plant spacing of approximately 15-20 cm may be maintained depending on the production system.

Nutrient management

Being a leafy vegetable, Bathua responds strongly to balanced nutrition, particularly nitrogen. Organic manures contribute to soil health and provide a favourable environment for vegetative growth. A basal application of 25–30 t/ha farmyard manure and N:P:K at 80:50:50 kg/ha has been recommended under improved production. Nitrogen supplementation after successive cuttings supports rapid regrowth. For farmer-level use, nutrient doses should be adjusted according to soil-test values, local recommendations and the expected number of harvests.

Irrigation and intercultural operations

Bathua has relatively modest irrigation requirements during the cool season. A light irrigation should be given immediately after transplanting, followed by irrigation at approximately 10–12 day intervals depending on soil type and weather conditions. Weed control during the early stages is important because the crop is grown for tender leaf biomass. Two or three weeding or hoeings during the crop period help maintain a clean and productive field.

Harvesting

The first harvest is generally available around 40-45 days after sowing or transplanting. Subsequent harvests can be taken at approximately 20-day intervals. Under suitable conditions, four to six cuttings may be possible before flowering reduces leaf quality. An average green leaf yield of around 35 t/ha can be obtained under improved production practices. Timely harvesting is particularly important in leafy vegetables. Tender, succulent leaves have better market appeal and eating quality, whereas delayed harvesting results in fibrous growth and declining palatability.

Future Prospects

Despite its potential, Bathua still requires greater attention from research, extension and food-processing sectors. Future efforts should focus on collecting and evaluating diverse germplasm, breeding cultivars for high leaf yield and delayed bolting, improving leaf texture and colour, enhancing micronutrient density and identifying types suitable for different agro-climatic regions. Standardized production packages are needed for regions beyond the traditional Bathua-growing areas. Greater research attention should also be given to extended-season production, protected cultivation, organic production systems and the development of cultivars suitable for baby-leaf markets.

Post-harvest research is equally important. Fresh leafy vegetables are highly perishable, and suitable packaging, cold-chain management, dehydration methods and minimally processed products could substantially increase the commercial value of bathua. Scientific work on processing already indicates that bathua can be incorporated into several conventional and novel foods, but its commercial exploitation remains limited. Most importantly, consumer awareness must improve. A crop cannot become commercially important merely because it is nutritious; it must also be visible, convenient and desirable to consumers. Linking traditional recipes with modern food products can help bathua find a place in both rural diets and urban markets.

Conclusion

Bathua is a striking example of an overlooked biological resource waiting to be rediscovered. What is often removed from fields as a weed is, in fact, a nutrient-rich leafy vegetable with considerable

potential for household nutrition, diversified farming and value-added food products. Its richness in vitamins, minerals, dietary fibre, quality protein and bioactive compounds makes it relevant to the challenge of hidden hunger. Its low-cost production, suitability for repeated harvesting and availability of high-yielding cultivars strengthen its agricultural potential. At the same time, opportunities for dehydration, fortification and functional food development can transform bathua from a seasonal local green into a higher-value commodity. The journey of bathua from weed to wealth requires coordinated attention from breeders, vegetable scientists, nutritionists, food technologists, extension workers and entrepreneurs. Promoting this humble winter green is not merely about reviving a traditional vegetable; it is about building a more diverse, nutritious and locally resilient food system.

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Fig. 1. Bathua plant showing characteristic foliage and flowering stage

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SYNTHETIC APOMIXIS IN CROP PLANTS: A GENETIC STRATEGY FOR FIXATION OF HYBRID VIGOR AND SUSTAINABLE SEED SYSTEMS

Bokka Kiranmayee* and Naresh Kumar Sahu

Department of Genetics and Plant Breeding, College of Agriculture,
Indira Gandhi Krishi Vishwavidyalya, Raipur, Chhattisgarh, India.¹

*Corresponding Email: kiranmayeeb2024@gmail.com

Abstract

Synthetic apomixis is an advanced genetic strategy to fix hybrid vigor (heterosis) in crop plants through clonal seed production. In conventional hybrids, genetic segregation during sexual reproduction prevents stable inheritance of superior traits. Synthetic apomixis addresses this limitation by integrating apomeiosis, parthenogenesis, and endosperm development. The MiMe (Mitosis instead of Meiosis) approach enables the formation of unreduced gametes via targeted mutations in key meiotic genes. Parthenogenesis is induced by regulators such as BBM1, which trigger embryo development without fertilization. Recent progress in crops like rice has demonstrated high-frequency clonal seed formation with stable transmission of hybrid traits. However, challenges including endosperm imbalance, reduced fertility, and regulatory constraints remain for large-scale agricultural deployment.

Keywords: Synthetic apomixis; Heterosis; MiMe strategy; Clonal seeds

Introduction

Heterosis, or hybrid vigor, is a fundamental biological phenomenon wherein hybrid offspring exhibit phenotypic superiority over their inbred parents in traits such as biomass, growth rate, and stress adaptability. This phenomenon has been central to global agricultural productivity for over a century. However, the primary limitation of hybrid crop production is the segregation of genotypes and phenotypes during sexual reproduction, which prevents the maintenance of these elite qualities in subsequent generations. Consequently, agricultural systems are locked into laborious and costly cycles of annual hybrid seed production.

Apomixis, a natural process of asexual reproduction through seeds, presents a theoretical solution by enabling the inheritance of the maternal genome without fertilization or genetic recombination. Because naturally apomictic traits are absent in major staple crops, and introgression from wild relatives has achieved limited success, molecular engineering has introduced synthetic apomixis a method designed to artificially assemble the components of apomictic propagation to permanently fix hybrid vigor.

The Biological Architecture of Natural Apomixis

In nature, apomixis occurs in two basic forms: sporophytic and gametophytic. Sporophytic apomixis involves the direct development of embryos from somatic cells of the ovule, often occurring concurrently with sexual reproduction, as seen in Citrus species. Gametophytic apomixis is characterized by the derivation of embryos from an unreduced embryo sac. This can occur via diplospory (where the embryo sac develops from a megaspore mother cell with suppressed meiosis) or apospory (where it originates from a somatic cell). A central challenge in agricultural biotechnology is mimicking these unreduced, clonal pathways in sexually reproducing crops.

Molecular Engineering of Synthetic Apomixis

The engineering of synthetic apomixis requires the precise molecular coordination of three critical reproductive steps: apomeiosis (the formation of unreduced female gametophytes), parthenogenesis or genome elimination (embryo development without a paternal genomic contribution), and the formation of a viable endosperm.

Apomeiosis via the MiMe Strategy

To bypass meiosis and prevent genetic recombination, researchers frequently employ the Mitosis instead of Meiosis (MiMe) strategy. MiMe requires the disruption of three specific events:

Inhibition of double-strand breaks (DSBs): Genes such as SPO11-1 or PRD1 are disabled to prevent chromosomal pairing and recombination.

Premature separation of sister chromatids: Subunits like REC8 are mutated to alter kinetochore orientation and chromatid cohesion during the first meiotic division.

Skipping the second meiotic division: Mutations in cell cycle regulators, such as OSD1, prevent the secondary division that typically halves the chromosome number. Together, these modifications convert meiosis into a mitotic-like division, yielding clonal diploid gametes that retain the exact genetic code of the parent.

Embryogenesis:

Genome Elimination and Parthenogenesis Once an unreduced egg cell is formed, it must develop into an embryo without true fertilization. Two primary methodologies are utilized:

Genome Elimination: This approach allows for fertilization but subsequently induces the degradation of the paternal chromosomes. This can be achieved by manipulating centromere-specific histones (e.g., CENH3 variants) or by inducing mutations in pollen-specific genes like MATRILINEAL (MTL), which trigger reactive oxygen species bursts and chromosome fragmentation in pollen.

Parthenogenesis: A more highly successful method involves the ectopic expression of specific trigger genes that artificially initiate embryo development from an unfertilized egg. Genes such as BABY BOOM (BBM1)—an AP2/ERF transcription factor—and PsASGR-BBML have demonstrated significant efficacy in inducing parthenogenesis in cereal crops like rice and maize.

Endosperm Formation:

The endosperm is a nutrient-rich tissue vital for seed viability. While autonomous endosperm development (occurring without fertilization) is observed in some natural apomicts, its molecular induction in crops is highly complex, often involving the manipulation of the FIS-PRC2 chromatin-modifying complex or auxin biosynthesis genes (e.g., OsYUC11). Currently, most synthetic apomixis systems rely on pseudogamy, wherein normal fertilization of the central cell is permitted solely to trigger endosperm growth, while the cloned embryo develops parthenogenetically alongside it.

Recent Empirical Advancements

The transition of synthetic apomixis from theory to empirical reality has seen its most profound successes in rice (*Oryza sativa*). By combining the MiMe triple mutation (pair1/rec8/osd1) with the egg-cell-specific expression of the OsBBM1 parthenogenesis gene, researchers have successfully produced clonal diploid seeds at frequencies exceeding 95% in hybrid rice. Crucially, these synthetic apomicts exhibited seed-setting rates comparable to wild-type plants, and the elite

hybrid vigor was stably transmitted across multiple generations with no observable phenotypic penalties.

Agricultural Implications and Future Challenges

The commercial realization of synthetic apomixis represents a paradigm shift for plant breeding. It promises the permanent fixation of heterosis, increased breeding efficiency by removing the need for continual parental line crossing, and the democratization of elite seeds for farmers in developing regions by lowering recurring input costs.

However, substantial biological and regulatory hurdles remain. Endosperm imbalance is a persistent issue, as conflicts between parthenogenetic embryo formation and central cell fertilization frequently lead to seed abortion. Furthermore, haploid induction methods relying on genome elimination suffer from drastically reduced plant fertility. Finally, as this technology is fundamentally dependent on advanced CRISPR/Cas9 genome editing, its deployment will necessitate navigating complex and variable global regulatory frameworks before entering the commercial agricultural market.

Conclusion

Synthetic apomixis effectively bridges the gap between classical hybrid breeding and modern molecular genetics. By resolving the inherent genetic instability of hybrid crops, the continued refinement of apomeiosis, parthenogenesis, and endosperm regulatory networks paves the way toward a more resilient, uniform, and efficient global agricultural system.

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HEALTH-PROMOTING AND THERAPEUTIC BENEFITS OF VARIOUS PARTS OF THE PALMYRAH TREE

Siva Sakthi T¹, Sabarinathan G² and Gomathy M³

¹Project Assistant, Dept. of Agri. Microbiology,
Agricultural College and Research Institute, , TNAU, Madurai

²Associate Professor, Dept. of Agri. Microbiology,
Agricultural College and Research Institute, , TNAU, Madurai

³Associate Professor, Dept. of Agri. Microbiology,
VOC Agricultural College and Research Institute, Killikum

*Corresponding Email: sivasakthit1997@gmail.com

Introduction

Borassus flabellifer L., widely known as the palmyrah palm and traditionally referred to as "Kalpaga Tharu" in Tamil culture, is a highly valued multipurpose tree that has sustained communities across South and Southeast Asia for generations. Renowned for its diverse economic, nutritional and medicinal importance, the palm provides food, traditional remedies, fibre and timber. Native to tropical Africa, it has become extensively established across West Africa, the Indian subcontinent and Southeast Asia. The tree offers a wide range of useful products, including sweet sap (neera and toddy), edible fruit pulp, starch-rich tubers, protein-rich haustoria and leaves that are extensively used in handicrafts and household articles. Beyond its traditional uses, the palmyrah palm has gained increasing attention as a valuable source of nutraceuticals and functional food ingredients. India is home to nearly 102 million palmyrah trees, with about half of the population located in Tamil Nadu, where the species plays a vital role in supporting rural livelihoods through the production and marketing of palm jaggery, toddy vinegar, fibre products, and other value-added commodities.

Therapeutic benefits derived from various parts of palmyra tree

Palmyrah Leaves

Palmyrah (*Borassus flabellifer* L.) leaves are recognized for their diverse therapeutic properties and have been traditionally used to alleviate inflammatory conditions such as arthritis. Scientific investigations have demonstrated that leaf extracts possess considerable antimicrobial and antifungal activities against a wide range of pathogenic microorganisms. In particular, methanolic extracts and acetone fractions have exhibited strong inhibitory effects against several bacterial and fungal strains. Furthermore, the leaves are rich in phenolic compounds that contribute to their potent antioxidant activity by effectively scavenging free radicals, with an efficacy comparable to that of ascorbic acid. Experimental studies have also reported significant inhibition of fungal growth, highlighting the potential of palmyrah leaves as a natural source of antimicrobial, antifungal, and antioxidant compounds with promising applications in the pharmaceutical and nutraceutical industries (Jamkhande *et al.*, 2016).

Young leaves

The juice extracted from young palmyrah leaves, when mixed with water, has traditionally been used as a natural remedy for the treatment of dysentery (Jerry, 2018).

Spadix

The ash obtained from the palmyrah spadix has traditionally been used as a herbal remedy for the management of acid reflux and hepatosplenomegaly (enlargement of the liver and spleen) (Allwin *et al.*, 2024).

Inflorescence

The palmyrah inflorescence possesses antacid and antiperiodic properties and is traditionally used to treat bilious fever, splenomegaly, and heartburn. It has also shown promising antidiabetic potential in scientific studies (Shrestha, 2023).

Staminate Flowers

Methanolic extracts of *Borassus flabellifer* staminate flowers have demonstrated significant antidiabetic activity by preventing sucrose-induced elevations in serum glucose levels, possibly due to the presence of steroidal compounds such as spirostane. In addition, these extracts have been reported to possess immunosuppressive properties (Shanmugalingam *et al.*, 2021).

Neera

Neera is a nutrient-rich natural beverage with numerous therapeutic benefits. It promotes healthy urination, supports digestion, helps regulate body temperature and is traditionally used to prevent jaundice. Owing to the presence of nicotinic acid (vitamin B₃) and riboflavin (vitamin B₂), it is considered beneficial for individuals with diabetes. Neera also functions as a natural tonic, diuretic, energizer, intestinal regulator, mucus-clearing and amoebicidal agent. Traditionally, it has been used to manage ulcers, gastric disorders, asthma, anemia and leprosy. Its rich composition of retinol (vitamin A), B-complex vitamins, natural sugars, minerals and micronutrients further enhances its nutritional and therapeutic value (Asha *et al.*, 2019).

Toddy

Traditionally, toddy has been used as a remedy for the treatment of ulcers (Shukla and Dubey, 2022).

Immature Palmyrah Fruit Pulp

Immature palmyrah fruit pulp is a rich source of bioactive compounds, containing high levels of phenolics (104 ± 0.02 µg gallic acid equivalents/100 mg) and flavonoids (98.45 ± 0.03 µg quercetin equivalents/100 mg), which contribute to its antioxidant potential (Renuka *et al.*, 2019).

Fruit

Palmyrah fruit is valued for its diverse medicinal and nutritional properties and has been traditionally used to manage thirst, indigestion, abdominal bloating, fever, skin ailments, excessive bleeding, general fatigue, and asthma-related disorders. It is also considered beneficial in treating hepatosplenomegaly, heartburn, and secondary syphilis. The fruit is a rich source of bioactive compounds, including alkaloids, terpenes, saponins, tannins, flavonoids, glycosides, phenols, sterols, gums, sugars, albuminoids, lipids, and vitamins A, B, and C. These phytochemicals impart antioxidant, anti-inflammatory, antimicrobial, and hydrating activities, thereby promoting digestive and cardiovascular health and supporting its use in traditional medicine, nutraceuticals, and cosmetic applications (Prasad *et al.*, 2023).

Mature Fruit Pulp

Mature palmyrah fruit pulp is a rich source of diverse bioactive phytochemicals, including furan derivatives, glucosides, fatty acids, sterols, and squalene, which contribute to its therapeutic

potential. The ethanolic extract of the fruit pulp has demonstrated significant antimicrobial activity against *Escherichia coli*, a common cause of urinary tract and intestinal infections, and *Staphylococcus aureus*, a major pathogen associated with skin and soft tissue infections. These findings highlight the potential of mature palmyrah fruit pulp as a natural source of antimicrobial and health-promoting compounds (Vengaiah *et al.*, 2021).

Pinnatu (Dried Fruit Pulp)

Pinnatu, a traditional product prepared by drying palmyrah fruit pulp, has been reported to help reduce blood glucose levels in individuals with early-stage type II diabetes, indicating its potential as a functional food with antidiabetic properties (Bandara *et al.*, 2010).

Seed and Seed Coat

Methanolic extracts of the *Borassus flabellifer* seed coat have demonstrated broad-spectrum antibacterial activity against *Staphylococcus aureus*, *Bacillus subtilis*, *Klebsiella pneumoniae*, and *Serratia marcescens*. In addition, the extracts exhibited significant cytotoxic activity by inhibiting the proliferation of HeLa cells in MTT assays at concentrations ranging from 32 to 750 µg/mL. These findings indicate that the seed coat is a promising source of natural antimicrobial and cytotoxic compounds with potential pharmaceutical applications, warranting further investigation.

Haustorium

Palmyrah haustorium contains over 50 bioactive compounds with antibacterial, antimicrobial, hepatoprotective, antiallergic, cardioprotective, diuretic, antioxidant, anti-inflammatory, and antineoplastic properties. Key constituents, including 5-hydroxymethylfurfural and D-glycero-D-galactoheptose, exhibit promising antioxidant, therapeutic, and anti-inflammatory activities (Sayanhika and selvakumar, 2024).

Young Roots

Young roots of the palmyrah (*Borassus flabellifer* L.) have been traditionally used in the treatment of respiratory disorders, jaundice, urinary tract infections, alopecia and pterygium. They exhibit anthelmintic, diuretic, cooling and nephroprotective properties, thereby supporting kidney function and providing therapeutic benefits against pulmonary ailments. In traditional practice, the roots are chopped, mixed with twice their volume of water, and sun-dried (*Suriya Pudam*) before use as a medicinal preparation (Jeery, 2018).

Roots

Palmyrah roots are a rich source of bioactive compounds, including phenolics, flavonoids, alkaloids, saponins, aldehydes, diterpenes, phytols, sterols, fatty acids, alkanes, alkenes, and ketones. Methanolic root extracts exhibit high phenolic (99.34 µg GAE/100 mg) and flavonoid (98.48 µg catechin equivalents/100 mg) contents, while the chloroform extract demonstrates strong antioxidant activity (129.6 µg BHT equivalents/100 mg). Both the root extract and root juice possess notable anti-inflammatory properties, highlighting their potential therapeutic value (Sahni *et al.*, 2014).

Bark

Palmyrah bark is traditionally used in oral healthcare. A decoction of the bark is prepared as a mouthwash, while bark charcoal mixed with salt serves as a natural dentifrice for maintaining oral hygiene (Mosae selvakumar, 2024).

Palm Sugar

Palm sugar is valued for its nutritional and therapeutic properties, helping to manage nutritional deficiencies and chronic diseases. It exhibits analgesic activity and is a good source of iron (5–10 mg/100 g), making it beneficial in the management of anemia. Additionally, it is traditionally used to support liver health and aid in detoxification (Sarkar *et al.*, 2023).

Conclusion

Palmyrah palm is a valuable multipurpose tree with remarkable therapeutic potential, as nearly every part of the plant possesses medicinal properties. Its leaves, roots, bark, flowers, fruits, sap, seed, haustorium and value-added products are rich sources of bioactive compounds, including phenolics, flavonoids, alkaloids, terpenes, saponins, sterols and vitamins, which exhibit antioxidant, antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, cardioprotective, and anticancer activities. These therapeutic attributes support the traditional use of palmyrah in managing a wide range of health conditions while highlighting its potential for developing functional foods, nutraceuticals, and natural pharmaceuticals. Although several studies have validated its medicinal properties, further phytochemical characterization, mechanistic investigations, and well-designed clinical studies are required to substantiate its efficacy and facilitate its integration into evidence-based healthcare systems.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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TRUE POTATO SEED (TPS): REVOLUTIONIZING AFFORDABLE AND DISEASE-FREE SEED SYSTEMS FOR SMALLHOLDER POTATO FARMERS

Sayani Das

Department of Agronomy, Faculty of Agriculture,
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal, India
Corresponding Email: sayani9916@gmail.com

Introduction

Potato is the world's third most important food crop after rice and wheat and plays a vital role in ensuring food and nutritional security. However, the availability and affordability of quality seed remain major constraints to potato production, particularly for smallholder farmers. Seed alone accounts for nearly 40–50% of the total cost of potato cultivation, and poor-quality planting material is one of the primary reasons for low productivity and yield instability (Buckseth *et al.*, 2022).

Traditionally, potatoes are propagated using seed tubers. While this method ensures crop uniformity and ease of cultivation, it also involves several challenges, including high transportation costs, seed degeneration and the accumulation of diseases. In recent years, True Potato Seed (TPS)—the botanical seed produced within potato berries—has emerged as a promising alternative. Although TPS was introduced and evaluated in India during the early 1980s (Almekinders *et al.*, 2009), advances in hybrid breeding, nursery management and seed production technologies have renewed interest in its adoption.

This article examines the advantages and limitations of both traditional seed tubers and TPS and discusses how an integrated seed system can benefit resource-constrained potato growers.

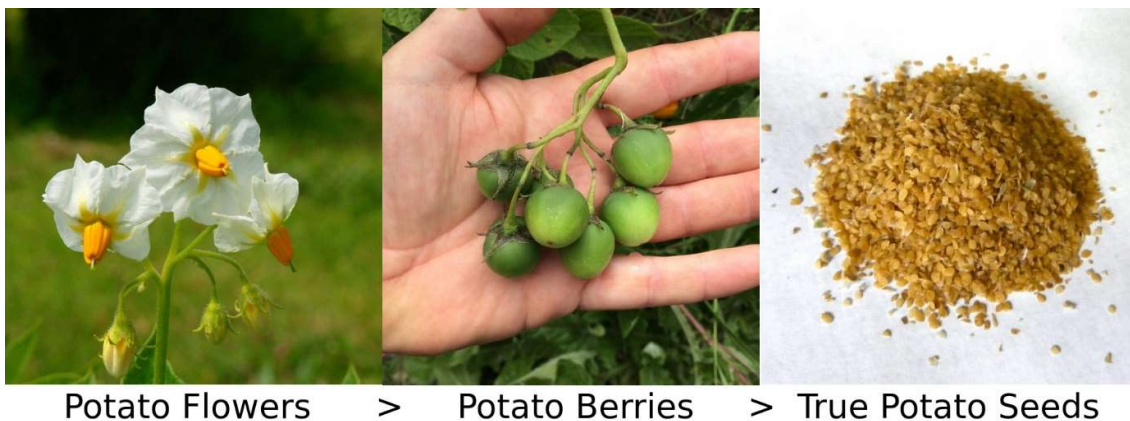


Fig 1: True Potato Seed (Credit: Cultivariable)

Traditional Seed Tubers: Strengths and Limitations

Why Farmers Prefer Seed Tubers

Seed tubers have served farmers reliably because they are:

- Genetically identical clones, ensuring uniformity in field performance.

- Easy to plant without special nursery skills.
- Familiar to farmers, requiring no specialised knowledge.
- Quick to establish, with no transplanting stage.
- Reliable in market-driven production, where uniform tuber size is essential.

For commercial growers supplying processing industries or structured markets, these advantages are critical.

But Seed Tubers Carry Hidden Costs

Why Farmers Prefer Seed Tubers

For generations, seed tubers have been the preferred planting material because they offer several practical advantages:

- Genetic uniformity due to clonal propagation
- Reliable field establishment and crop performance
- Ease of planting without the need for nursery raising
- Familiarity among farmers and extension personnel
- Production of uniform tubers suitable for commercial markets and processing industries

These attributes make seed tubers highly suitable for intensive and market-oriented potato production systems.

Hidden Costs of Seed Tubers

Despite their advantages, seed tubers have several inherent limitations:

- Accumulation of viral diseases over successive generations
- High transportation and storage costs because of their bulky nature
- Requirement for cold storage facilities to maintain seed quality
- Susceptibility to rotting, mechanical damage and pest infestation
- High seed cost per hectare
- Rapid seed degeneration requiring frequent replacement with certified seed

Research indicates that seed degeneration caused primarily by viral infections can reduce potato yields by 20–80%, depending on environmental conditions and seed source quality (Kumar *et al.*, 2024).

Thus, while seed tubers perform well in areas with access to certified seed and storage infrastructure, they often become a major economic burden for smallholders in remote and resource-constrained regions.

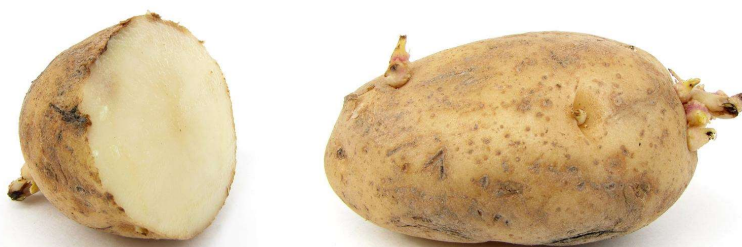


Fig 2: Potato seed tuber (Credit: Feedipedia)

True Potato Seed (TPS)**Why TPS Is Attracting Global Attention**

TPS offers several advantages that directly address the challenges associated with conventional seed tubers:

1. Disease-Free Planting Material

As botanical seeds, TPS generally does not transmit most tuber-borne viral diseases, providing a clean starting point for crop establishment.

2. Lower Seed Cost

Only a few grams of TPS are sufficient to plant one hectare, dramatically reducing seed expenditure.

3. Easy Storage and Transportation

Unlike bulky seed tubers, TPS requires minimal storage space and can be transported easily at negligible cost.

4. Enhanced Adaptability

Many TPS populations exhibit greater tolerance to drought, heat stress and certain diseases, making them suitable for challenging production environments.

5. Longer Storage Life

TPS can remain viable for 5–10 years when stored under cool and dry conditions, offering significant advantages for seed security.

Modern TPS Hybrids: Addressing Earlier Limitations

Earlier open-pollinated TPS populations often produced highly variable plants and tubers, limiting their commercial acceptance. However, recent advances in hybrid breeding have resulted in TPS varieties with improved uniformity, higher productivity and better adaptation to diverse agro-climatic conditions.

Several breeding programmes in India, Peru, China and Bangladesh have demonstrated the potential of modern TPS hybrids for sustainable potato production.

Challenges Associated with TPS

Despite its advantages, TPS adoption is not without challenges:

- Requirement for nursery raising and seedling management
- Greater technical skill and labour input
- Longer crop duration, often extending 20–30 days beyond conventional crops
- Initial variability in tuber size and shape during the first generation

These factors may discourage farmers seeking immediate marketable produce. However, TPS-grown seedlings can produce healthy mini-tubers that serve as excellent seed material for subsequent seasons.

Comparative Evaluation of TPS and Seed Tubers**Table 1. Seed Tubers vs TPS: A Comparative Overview**

Feature	Traditional Seed Tubers	True Potato Seed (TPS)
Disease load	High	Negligible
Seed cost	Very high	Very low
Transport and storage	Difficult and costly	Easy and economical

Feature	Traditional Seed Tubers	True Potato Seed (TPS)
Uniformity	Excellent	Moderate to high (hybrids)
Labour requirement	Low	Higher
Shelf life	Short	Long
Suitability for remote areas	Low	High
Seed degeneration	Common	Absent

An Integrated Seed Strategy: The Best of Both Worlds

Increasingly, researchers and development agencies are advocating a two-step seed system that combines the strengths of TPS and seed tubers:



Fig. 3. Integrated TPS-based seed production system for generating disease-free seed tubers and commercial potato crops.

Year 1

Use TPS to produce disease-free mini-tubers.

Years 2–3

Plant the mini-tubers as seed tubers for commercial production.

This approach provides:

- Reduced seed costs
- High crop vigour
- Minimal disease pressure
- Improved seed quality
- Greater yield stability
- Uniform marketable produce

Such an integrated strategy combines the economic advantages of TPS with the agronomic benefits of conventional seed tubers.

Which Option is Best for Small Farmers?

TPS May Be More Suitable For Farmers Who:

- Face high seed procurement costs
- Live in remote areas with expensive transportation
- Frequently experience virus-related yield losses
- Seek greater seed self-reliance
- Possess the capacity to manage nurseries

Seed Tubers May Be More Suitable For Farmers Who:

- Require immediate and uniform crop establishment
- Produce for commercial or processing markets
- Have reliable access to certified seed sources
- Prefer simpler cultivation practices without nursery management

Conclusion

True Potato Seed should not be viewed as a complete replacement for conventional seed tubers. Rather, it represents a complementary technology capable of overcoming many of the economic and logistical constraints faced by smallholder potato farmers.

By enabling the production of disease-free mini-tubers at a fraction of the cost of conventional seed, TPS offers a pathway toward greater seed security, reduced production costs and improved sustainability. The integration of TPS-derived mini-tubers with traditional seed systems presents a practical and scalable approach for enhancing potato productivity in developing countries.

As breeding programmes continue to develop more uniform, high-yielding and climate-resilient TPS hybrids, this technology is poised to become one of the most transformative innovations in potato cultivation. Sometimes, the smallest seed can create the biggest change in agricultural sustainability and farmer livelihoods.

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METAGENOMICS AND MICROBIOME ENGINEERING IN AQUACULTURE: A NEW ERA OF DISEASE CONTROL AND PRODUCTIVITY ENHANCEMENT

Vaishali and Aashi Saldhi

University of Lucknow, Lucknow, Uttar Pradesh, India

*Corresponding Email: vijaychaudhary30358@gmail.com

Abstract

Aquaculture has become one of the fastest-growing food production sectors globally, contributing significantly to food security, nutrition, employment, and economic growth. However, disease outbreaks, antimicrobial resistance (AMR), poor water quality, and environmental degradation continue to threaten sustainable aquaculture production. Recent advances in metagenomics and microbiome engineering have revolutionized the understanding of microbial communities associated with fish, shrimp, water, and sediments. Unlike conventional culture-based methods, metagenomics enables comprehensive analysis of microbial diversity, functional genes, and pathogen dynamics directly from environmental samples, providing rapid and accurate disease surveillance. Simultaneously, microbiome engineering focuses on manipulating beneficial microbial communities through probiotics, prebiotics, synbiotics, biofloc technology, and other microbiome-based interventions to improve fish health, immunity, growth, and disease resistance. These emerging technologies are transforming fisheries health management by reducing dependence on antibiotics and promoting environmentally sustainable aquaculture. This article discusses the principles of metagenomics, the significance of aquatic microbiomes, major applications in aquaculture, and the future potential of microbiome engineering for enhancing productivity and disease control.

Keywords: Metagenomics, Microbiome Engineering, Aquaculture, Fish Health, Disease Control, Sustainable Aquaculture, Gut Microbiome, Bioinformatics.

Introduction

Aquaculture currently supplies more than half of the aquatic animals consumed worldwide and has become one of the fastest-growing food production sectors, playing a vital role in global food security and economic development (FAO, 2024). In India, fisheries and aquaculture contribute substantially to national food production, rural employment, and export earnings. However, the rapid intensification of aquaculture has increased the occurrence of infectious diseases, deterioration of water quality, antimicrobial resistance (AMR), and environmental pollution, resulting in considerable economic losses (FAO, 2022). Traditionally, disease diagnosis in aquaculture has relied on microbial culture techniques and targeted molecular methods. Although effective for detecting known pathogens, these approaches often fail to identify unculturable microorganisms or characterize the complete microbial community associated with aquatic ecosystems. Advances in next-generation sequencing (NGS) have led to the development of metagenomics, which enables comprehensive analysis of microbial communities directly from environmental samples without the need for laboratory cultivation. This technology provides valuable insights into microbial diversity, functional genes, pathogen ecology, and antibiotic resistance genes present in aquaculture systems (Macedo *et al.*, 2024). In addition to

metagenomics, the concept of microbiome engineering has emerged as a promising strategy for sustainable aquaculture. Instead of eliminating microorganisms, microbiome engineering focuses on modifying microbial communities to increase the abundance of beneficial microbes while suppressing opportunistic pathogens. Such approaches improve fish health, enhance nutrient utilization, strengthen immune responses, and reduce dependence on antibiotics (Gupta *et al.*, 2025). Together, metagenomics and microbiome engineering represent a paradigm shift in aquaculture health management. Their integration with artificial intelligence, bioinformatics, and precision aquaculture is expected to transform disease surveillance, environmental monitoring, and farm productivity while supporting sustainable aquaculture development.

Understanding Metagenomics

Metagenomics is the study of the collective genetic material (metagenome) obtained directly from environmental samples such as pond water, sediments, biofilms, fish gut contents, skin mucus, or gill tissues without isolating or culturing individual microorganisms. Unlike conventional microbiological techniques, metagenomics captures the complete microbial community, including bacteria, archaea, fungi, viruses, and protozoa, providing a comprehensive understanding of microbial diversity and ecosystem function (Grossart *et al.*, 2020). Modern metagenomic analysis is primarily based on high-throughput sequencing technologies such as Illumina, Oxford Nanopore, and PacBio platforms. After DNA extraction, sequencing data are analysed using advanced bioinformatics tools to identify microbial taxa, characterize functional genes, detect virulence factors, and evaluate antimicrobial resistance genes. This approach allows researchers to investigate both microbial composition and metabolic potential simultaneously, making metagenomics an indispensable tool for aquaculture research (Macedo *et al.*, 2024). Compared with traditional culture-based methods, metagenomics provides several important advantages:

- Detection of both culturable and non-culturable microorganisms.
- Simultaneous identification of beneficial and pathogenic microbes.
- Early detection of emerging pathogens.
- Characterization of antimicrobial resistance genes (ARGs).
- Functional analysis of microbial metabolic pathways.
- Comprehensive monitoring of environmental microbial communities.

These advantages have made metagenomics one of the most powerful molecular tools for disease surveillance and environmental assessment in modern aquaculture.

Aquatic Microbiome and Its Importance

The aquatic microbiome refers to the diverse community of microorganisms inhabiting fish, shrimp, pond water, sediments, bioflocs, biofilms, and aquatic plants. These microorganisms interact continuously with their host and surrounding environment, influencing digestion, nutrient cycling, immunity, metabolism, water quality, and disease resistance (Gupta *et al.*, 2025). Among these microbial communities, the gut microbiome is particularly important because it assists in nutrient digestion, synthesis of vitamins, production of digestive enzymes, and stimulation of the host immune system. Beneficial bacteria such as *Lactobacillus*, *Bacillus*, *Lactococcus*, and *Pseudomonas* contribute to intestinal health by producing antimicrobial compounds, competing with pathogens for nutrients and attachment sites, and modulating immune responses. Conversely, disturbances in microbial balance (dysbiosis) may facilitate the proliferation of opportunistic pathogens such as *Aeromonas*, *Vibrio*, and *Edwardsiella*, increasing disease susceptibility (Gupta *et al.*, 2025). The pond-water microbiome also plays a critical role in

maintaining ecosystem stability. Microbial communities participate in nitrogen transformation, organic matter degradation, phosphorus cycling, and detoxification of harmful metabolites, thereby improving water quality and supporting sustainable fish production. Recent metagenomic studies have demonstrated that changes in microbial community structure often occur before visible disease outbreaks, making the microbiome an important indicator of farm health (Liu *et al.*, 2024).

Applications of Metagenomics in Aquaculture

Early Disease Detection and Pathogen Surveillance

One of the most significant applications of metagenomics is the rapid identification of pathogenic microorganisms before the appearance of clinical signs. Conventional diagnostic methods often require isolation and cultivation of pathogens, which can be time-consuming and ineffective for fastidious microorganisms. Metagenomic sequencing overcomes these limitations by detecting microbial DNA directly from pond water, sediments, or infected fish tissues (Macedo *et al.*, 2024). Metagenomics enables simultaneous detection of bacterial, viral, fungal, and parasitic pathogens while also identifying virulence genes and antimicrobial resistance genes. Continuous microbial surveillance facilitates early disease warning systems, allowing farmers to implement preventive management strategies before severe outbreaks occur. This approach significantly reduces mortality, minimizes economic losses, and enhances biosecurity in aquaculture farms (Macedo *et al.*, 2024).

Monitoring Water Quality and Environmental Health

Metagenomic analysis has become an effective tool for monitoring microbial dynamics in aquaculture ponds and surrounding aquatic environments. Changes in microbial community composition often reflect alterations in water quality, nutrient loading, organic pollution, and environmental stress (Liu *et al.*, 2024). Through sequencing-based monitoring, researchers can evaluate nitrogen cycling microorganisms, sulphur-metabolizing bacteria, harmful algal-associated microbes, and antibiotic resistance genes. Such information enables farmers to assess ecosystem health, optimize pond management practices, and minimize environmental impacts while improving production efficiency.

Microbiome Engineering: A Novel Strategy for Sustainable Aquaculture

Microbiome engineering is an emerging approach that aims to manipulate microbial communities associated with fish, shrimp, and aquaculture environments to improve host health, disease resistance, and production performance. Unlike conventional disease control strategies that primarily rely on antibiotics and chemical therapeutics, microbiome engineering enhances the abundance and activity of beneficial microorganisms while suppressing opportunistic pathogens through ecological and biological interventions (Gupta *et al.*, 2025). The healthy microbiome serves as the first line of defense against infectious diseases by competing with pathogens for nutrients and attachment sites, producing antimicrobial compounds, stimulating immune responses, and maintaining intestinal homeostasis. Advances in metagenomics and bioinformatics now allow researchers to identify key microbial taxa associated with healthy aquatic animals, making it possible to design targeted microbiome-based interventions for sustainable aquaculture (Liu *et al.*, 2024).

Probiotics and Prebiotics

Probiotics are live beneficial microorganisms that confer health benefits when administered in adequate amounts. In aquaculture, commonly used probiotic genera include *Bacillus*,

Lactobacillus, *Lactococcus*, *Pediococcus*, *Enterococcus*, and *Pseudomonas*. These beneficial bacteria improve digestive enzyme activity, nutrient utilization, immune responses, and disease resistance while inhibiting pathogenic microorganisms through competitive exclusion and production of antimicrobial metabolites (Amenyogbe, 2023). Prebiotics are non-digestible dietary ingredients such as fructooligosaccharides (FOS), mannan-oligosaccharides (MOS), β -glucans, and inulin that selectively stimulate the growth of beneficial gut microorganisms. The combined use of probiotics and prebiotics (synbiotics) further enhances gut microbial balance, improves intestinal integrity, and increases growth performance under intensive culture conditions (De Marco *et al.*, 2023).

Biofloc Technology as Microbiome Engineering

Biofloc technology (BFT) represents one of the most successful examples of microbiome engineering in aquaculture. Bioflocs consist of beneficial microbial aggregates composed of bacteria, algae, protozoa, fungi, and organic particles that continuously recycle nitrogenous wastes into microbial biomass. Besides improving water quality by reducing ammonia and nitrite concentrations, bioflocs provide an additional source of microbial protein, vitamins, digestive enzymes, and immunostimulatory compounds for cultured fish and shrimp. Metagenomic studies have shown that biofloc systems harbor diverse beneficial microbial communities capable of suppressing pathogenic bacteria while improving feed utilization and growth performance (Martinez *et al.*, 2023). Consequently, biofloc technology reduces water exchange requirements, minimizes environmental pollution, and supports sustainable aquaculture.

Bacteriophage Therapy

The increasing prevalence of antimicrobial resistance has encouraged researchers to explore bacteriophages as an alternative disease control strategy. Bacteriophages are viruses that specifically infect and destroy bacterial pathogens without affecting beneficial microorganisms. Metagenomic analysis facilitates the identification and characterization of naturally occurring bacteriophages within aquaculture environments. Phage therapy has shown promising results against important fish pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., and *Edwardsiella* spp., reducing disease incidence while avoiding the adverse environmental impacts associated with antibiotic use (FAO, 2024). Although commercial applications remain under development, phage therapy represents a promising component of future microbiome engineering programmes.

Benefits of Metagenomics and Microbiome Engineering

The integration of metagenomics and microbiome engineering offers several advantages for modern aquaculture (Table 1). These technologies improve disease diagnosis, strengthen preventive health management, and support environmentally sustainable fish production. Major benefits include:

- Early detection of bacterial, viral, fungal, and parasitic pathogens before disease outbreaks.
- Comprehensive analysis of beneficial and harmful microbial communities.
- Identification of antimicrobial resistance (AMR) genes and virulence factors.
- Improved fish growth, feed efficiency, and nutrient utilization.
- Enhanced immune responses and disease resistance.
- Reduced dependence on antibiotics and chemical therapeutics.
- Better water quality management through microbial ecosystem monitoring.
- Increased farm productivity and profitability.
- Promotion of environmentally sustainable and climate-resilient aquaculture.

Together, these advantages make microbiome-based technologies powerful tools for precision aquaculture and responsible fisheries management (FAO, 2022; Gupta *et al.*, 2025).

Table 1. Major Applications of Metagenomics and Microbiome Engineering in Aquaculture

Technology	Major Application	Benefits
Metagenomics	Microbial diversity analysis	Identification of beneficial and pathogenic microorganisms
Next-Generation Sequencing (NGS)	Detection of unculturable microbes	Rapid and comprehensive pathogen identification
Gut Microbiome Analysis	Fish health assessment	Improved digestion, immunity, and nutrient utilization
Water Microbiome Monitoring	Water quality surveillance	Early detection of environmental changes
Probiotics	Beneficial microbial supplementation	Enhanced growth and disease resistance
Prebiotics & Synbiotics	Gut microbiome modulation	Improved intestinal health and immune function
Biofloc Technology	Microbial ecosystem engineering	Better water quality and reduced feed costs
Bacteriophage Therapy	Biological control of bacterial pathogens	Reduced antibiotic use and antimicrobial resistance

Challenges and Limitations

Despite their enormous potential, several challenges restrict the large-scale application of metagenomics and microbiome engineering in aquaculture. High-throughput sequencing instruments, advanced laboratory infrastructure, and bioinformatics expertise remain expensive and inaccessible to many developing countries. Interpretation of metagenomic datasets requires specialized computational tools and skilled personnel, making routine implementation difficult for many diagnostic laboratories. Furthermore, microbial communities vary according to fish species, geographical location, water quality, farming practices, and climatic conditions, making universal microbiome manipulation strategies challenging (Liu *et al.*, 2024). Regulatory issues, standardization of analytical protocols, limited field validation, and high implementation costs also restrict commercial adoption. Future research should therefore focus on developing affordable sequencing technologies, standardized microbiome databases, and farmer-friendly diagnostic platforms.

Future Prospects

The future of aquaculture will increasingly depend on precision health management supported by metagenomics, microbiome engineering, artificial intelligence (AI), machine learning, and bioinformatics. Continuous sequencing of pond water, sediment, and fish microbiomes may soon enable real-time disease surveillance and predictive health management systems. Artificial intelligence combined with metagenomic datasets will facilitate early prediction of disease outbreaks, optimization of probiotic formulations, and personalized microbiome management strategies for different fish species. CRISPR-based microbial engineering, synthetic biology, and next-generation probiotics may further revolutionize disease prevention and productivity enhancement in aquaculture (Gupta *et al.*, 2025). These innovations are expected to reduce

antimicrobial resistance, improve environmental sustainability, strengthen biosecurity, and support global food security through healthier and more productive aquaculture systems.

Conclusion

Metagenomics and microbiome engineering have introduced a new paradigm in aquaculture by shifting disease management from treatment to prevention. Unlike conventional diagnostic methods, metagenomics provides comprehensive information on microbial diversity, pathogen ecology, functional genes, and antimicrobial resistance directly from environmental samples. Simultaneously, microbiome engineering utilizes beneficial microorganisms to improve fish health, strengthen immunity, enhance feed utilization, and suppress pathogenic microbes. The integration of these technologies with bioinformatics, artificial intelligence, and precision aquaculture will enable rapid disease diagnosis, sustainable production, and environmentally responsible farming practices. Continued research, technological advancement, and collaboration among scientists, extension agencies, and fish farmers will be essential for translating microbiome research into practical field applications. Ultimately, metagenomics and microbiome engineering are expected to play a pivotal role in achieving sustainable aquaculture, improved productivity, and global food security.

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WOMEN ENTREPRENEURSHIP IN FISHERIES VALUE ADDITION: A PATHWAY TO SUSTAINABLE LIVELIHOODS AND BLUE ECONOMY

B. Deepika* and P. Ganesan

Department of Fish Processing Technology, Fisheries College and Research Institute,
Thoothukudi – 628 008

Corresponding Email: deepikabaskar143@gmail.com

Abstract

Women play a vital role in the fisheries sector, particularly in post-harvest activities such as processing, preservation, marketing, and value addition. Fisheries value addition has emerged as an effective strategy to enhance the quality, shelf life, marketability, and profitability of fish and fishery products while reducing post-harvest losses. With increasing consumer demand for safe, nutritious, convenient, and ready-to-eat seafood products, women entrepreneurs have significant opportunities to establish successful micro, small, and medium enterprises. Through innovative processing techniques, hygienic packaging, branding, and digital marketing, women can transform traditional fisheries activities into sustainable businesses that generate employment and improve household incomes. Government initiatives such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY), National Fisheries Development Board (NFDB), PM Formalisation of Micro Food Processing Enterprises (PMFME), and Self-Help Group (SHG)-based interventions have further strengthened women's participation in fisheries entrepreneurship. This article discusses the importance of women entrepreneurship in fisheries value addition, highlights potential business opportunities, examines the challenges faced by women entrepreneurs, and explores strategies to promote sustainable and inclusive growth in the fisheries sector. Empowering women through skill development, financial support, technological adoption, and market access can significantly contribute to livelihood security, rural development, and the realization of India's Blue Economy.

Keywords: Women entrepreneurship, Fisheries value addition, Seafood processing, Self-Help Groups (SHGs), Blue Economy, Fish processing, Rural livelihoods, Food safety, Value-added fish products, Sustainable development.

Introduction

India is one of the world's leading fish-producing nations, with the fisheries sector contributing significantly to food security, nutritional well-being, employment generation, and export earnings. According to the Department of Fisheries, the sector supports the livelihoods of more than 28 million people, directly and indirectly. While fish production has increased considerably over the past decade, a substantial proportion of the harvest is still marketed as fresh fish, limiting income opportunities for fishers and processors. One of the most effective ways to enhance profitability is value addition. Value addition involves transforming raw fish into attractive, convenient, nutritious, and marketable products through processing, packaging, branding, and preservation. Instead of selling fresh fish at fluctuating market prices, entrepreneurs can produce high-value products that command better prices and have longer shelf lives. Women have always been an integral part of India's fisheries sector. Traditionally, they have engaged in fish drying, cleaning, peeling, sorting, curing, processing, and marketing. Despite their immense contribution, much of their work has

remained unrecognized and confined to the informal sector. Today, with increasing awareness, improved access to technology, government support, and expanding markets, women are emerging as successful entrepreneurs in fisheries value addition. Women-led enterprises not only improve household income but also create employment opportunities, reduce post-harvest losses, strengthen food security, and contribute to the nation's Blue Economy. Their participation is transforming fisheries into a more inclusive and sustainable sector.

Women: The Driving Force Behind Fisheries Value Addition

Women possess exceptional skills in food preparation, quality maintenance, hygiene, product innovation, and customer relations. These strengths make them ideal entrepreneurs in fish processing and value-added seafood production.

Across India's coastal and inland regions, women actively participate in:

- Fish cleaning and dressing
- Fish drying and curing
- Preparation of fish pickles
- Seafood snack production
- Fish powder manufacturing
- Fish marketing
- Packaging and labeling
- Quality control
- Small-scale seafood processing
- Retail and online sales

With appropriate training and financial support, these traditional skills can be transformed into profitable business ventures. Women entrepreneurs also play a crucial role in preserving indigenous fish products and promoting local culinary traditions. Many regional fish delicacies prepared by women are now gaining recognition in urban markets due to increasing consumer demand for authentic and nutritious foods.

Understanding Fisheries Value Addition

Value addition refers to any activity that increases the economic value, quality, convenience, nutritional profile, or shelf life of fish and fishery products. It involves converting low-value or underutilized fish species into premium products that appeal to modern consumers.

The process includes:

- Cleaning and dressing
- Filleting
- Deboning
- Marination
- Cooking
- Drying
- Smoking
- Pickling
- Freezing
- Packaging
- Branding
- Product diversification

Value addition benefits every stakeholder in the fisheries value chain.

Benefits of Value Addition

- Higher income for fishers and processors
- Better utilization of low-value fish species
- Reduction in post-harvest losses
- Longer product shelf life
- Improved food safety and hygiene
- Increased employment opportunities
- Better consumer acceptance
- Enhanced export potential
- Promotion of entrepreneurship
- Sustainable use of marine resources

Instead of selling one kilogram of raw fish at a modest price, entrepreneurs can convert it into fish cutlets, fish pickles, smoked fish, or ready-to-cook fillets that fetch significantly higher returns.

Business Opportunities for Women Entrepreneurs

The fisheries sector offers a wide range of entrepreneurial opportunities requiring relatively low investment. Many enterprises can be started from home with basic equipment and proper training.

Fish Pickle Production

Fish pickle is one of the most popular value-added seafood products in India. It has excellent consumer acceptance and a relatively long shelf life when prepared under hygienic conditions.

Popular fish species include:

- Tuna
- Seer fish
- Mackerel
- Sardine
- Tilapia
- Catfish

Fish pickles are increasingly marketed through supermarkets, exhibitions, online platforms, and women's self-help groups.

Ready-to-Eat Seafood Products

Busy lifestyles have increased the demand for convenient foods.

Women entrepreneurs can manufacture:

- Fish curry
- Fish biryani
- Fish cutlets
- Fish fingers
- Fish nuggets
- Fish kebabs
- Fish balls
- Fish soup

These products require minimal preparation by consumers and are highly suitable for urban markets.

Ready-to-Cook Products

Consumers increasingly prefer products that reduce cooking time while maintaining freshness and quality.

Popular products include:

- Fish fillets
- Fish steaks
- Marinated fish
- Breaded fish
- Fish burger patties
- Fish sausages
- Fish mince
- Fish fingers

Vacuum packaging and refrigerated storage further improve shelf life and marketability.

Dry Fish and Traditional Products

Dry fish has been consumed in India for centuries and remains an important source of protein in many coastal and tribal communities. Modern hygienic drying methods have significantly improved product quality.

Women can establish enterprises producing:

- Solar-dried fish
- Hygienically dried shrimp
- Dried anchovies
- Salted fish
- Smoked fish

Improved packaging and branding enable these traditional products to reach premium markets.

Fish-Based Snacks

The growing snack food market presents exciting opportunities.

Innovative products include:

These products combine nutrition with convenience and appeal to health-conscious consumers.

- Fish chips
- Fish crackers
- Fish papad
- Fish wafers
- Fish noodles
- Fish pasta
- Fish biscuits

Protein-rich fish snacks for children

Fish Processing By-products: Waste to Wealth

Nearly 30–40% of fish processing results in by-products such as heads, bones, skin, scales, and viscera. Instead of discarding these materials, women entrepreneurs can convert them into valuable products.

Examples include:

- Fish meal
- Fish silage
- Organic fertilizer
- Fish collagen
- Fish gelatin
- Fish oil

- Calcium powder
- Pet food ingredients

This approach supports the circular economy by reducing waste and generating additional income.

Marine-Based Functional Foods

Consumers are increasingly seeking foods that provide health benefits beyond basic nutrition.

Women entrepreneurs can explore products enriched with marine bioactive compounds such as:

- Omega-3-rich foods
- Fish protein powder
- Fish collagen supplements
- Seaweed-fortified foods
- Nutraceutical products

Such products cater to health-conscious consumers and command premium prices.

Role of Self-Help Groups (SHGs) in Fisheries Entrepreneurship

Self-Help Groups (SHGs) have emerged as one of the most effective platforms for empowering women in rural and coastal communities. By working collectively, women can overcome financial constraints, share responsibilities, and establish sustainable fisheries-based enterprises. SHGs have successfully transformed many small household activities into profitable micro-enterprises by adopting improved processing technologies, attractive packaging, and organized marketing systems.

Women SHGs are actively involved in fish pickle preparation, hygienic dry fish production, shrimp processing, fish snack manufacturing, ornamental fish culture, seafood catering, and retail marketing. Collective production helps reduce production costs, ensures uniform quality, and increases bargaining power while purchasing raw materials and selling finished products.

Advantages of SHGs include:

- Easy access to bank credit and government subsidies
- Collective procurement of raw materials
- Shared processing facilities and equipment
- Better marketing and brand promotion
- Capacity building through training programmes
- Increased confidence and leadership among women
- Employment generation within the community

The SHG model has proven that when women work together, they can successfully compete with larger commercial enterprises while improving the socio-economic status of their families.

Government Support for Women Entrepreneurs

Recognizing the importance of women in fisheries, the Government of India and various state governments have introduced several programmes to encourage entrepreneurship and value addition.

Pradhan Mantri Matsya Sampada Yojana (PMMSY)

PMMSY is one of the flagship schemes aimed at developing the fisheries sector through infrastructure development, modernization, processing, value addition, cold chain facilities, and entrepreneurship promotion. The scheme encourages women entrepreneurs to establish fish processing units, retail outlets, and value-added product manufacturing units.

National Fisheries Development Board (NFDB)

NFDB promotes sustainable fisheries development by supporting skill development, infrastructure creation, quality improvement, processing technologies, and market development. Women entrepreneurs receive technical guidance and financial assistance under various programmes.

PM Formalisation of Micro Food Processing Enterprises (PMFME)

This scheme supports micro food processing units through financial assistance, technology upgradation, branding, and marketing support. Fisheries-based enterprises, including fish pickle and seafood snack units, are eligible under this programme.

DAY-NRLM

The Deendayal Antyodaya Yojana–National Rural Livelihoods Mission empowers rural women through SHGs by facilitating entrepreneurship, skill development, and financial inclusion.

MUDRA Loans

Micro Units Development and Refinance Agency (MUDRA) loans provide financial assistance to small entrepreneurs for starting or expanding fisheries-based enterprises without excessive collateral requirements. In addition, institutions such as ICAR-Central Institute of Fisheries Technology (ICAR-CIFT), Krishi Vigyan Kendras (KVKs), fisheries colleges, and state fisheries departments regularly organize training programmes on fish processing, packaging, quality assurance, and entrepreneurship development.

Importance of Food Safety and Quality

Consumers today expect seafood products that are safe, hygienic, nutritious, and free from contamination. Therefore, maintaining quality throughout processing is essential for building consumer trust and ensuring repeat purchases. Women entrepreneurs should adopt Good Manufacturing Practices (GMP), Good Hygienic Practices (GHP), and sanitation protocols during processing. Clean water, fresh raw materials, hygienic equipment, proper personal hygiene, and pest control are fundamental requirements.

Quality can be further enhanced through:

- Proper icing and cold storage
- Hygienic handling of fish
- Scientific preservation methods
- Moisture-proof packaging
- Appropriate labeling
- Batch coding and traceability
- Regular quality testing

Obtaining food safety certification and complying with national standards enhances market credibility and opens opportunities for supplying products to supermarkets and institutional buyers.

Branding, Packaging and Marketing

Many excellent products fail commercially because of poor packaging and weak marketing strategies. Attractive branding creates product identity and helps consumers recognize and trust a product.

A good package should:

- Protect the product from contamination

- Preserve freshness and shelf life
- Prevent moisture absorption
- Display nutritional information
- Include manufacturing and expiry dates
- Carry attractive labels and logos

Eco-friendly packaging materials are increasingly preferred by environmentally conscious consumers and enhance the product's appeal. Digital marketing has become an affordable and powerful tool for small entrepreneurs. Social media platforms, WhatsApp Business, online marketplaces, and e-commerce websites enable women to reach customers far beyond their local markets. Online payments, home delivery services, and customer reviews further strengthen business growth. Participation in food exhibitions, farmers' markets, seafood festivals, and trade fairs also helps entrepreneurs showcase their products and build valuable business networks.

Success Story: From Traditional Skills to Modern Enterprise

Consider the example of a coastal women's Self-Help Group that traditionally prepared dried fish for household consumption. After receiving training from the fisheries department, the group adopted hygienic drying techniques, improved packaging, developed a unique brand name, and obtained food safety registration. The group diversified its products by introducing fish pickles, shrimp masala mix, fish cutlets, and ready-to-cook fish fillets. Through social media marketing and participation in local exhibitions, they expanded their customer base to nearby cities. Within a few years, the enterprise generated regular employment for several women, increased household incomes, reduced dependence on middlemen, and inspired other women in the village to establish similar businesses. Such examples demonstrate how scientific knowledge, entrepreneurial skills, and collective effort can transform traditional occupations into sustainable enterprises.

Challenges Faced by Women Entrepreneurs

Despite significant progress, several challenges continue to hinder the growth of women-led fisheries enterprises.

Major constraints include:

- Limited access to institutional finance
- High cost of processing equipment
- Inadequate cold chain infrastructure
- Lack of modern packaging facilities
- Limited awareness of food safety regulations
- Difficulty in obtaining market information
- Seasonal fluctuations in fish availability
- Competition from established brands
- Transportation and logistics challenges
- Balancing family responsibilities with business activities

Addressing these challenges requires coordinated efforts from government agencies, research institutions, financial organizations, and extension services.

Strategies for Sustainable Success

Women entrepreneurs can strengthen their enterprises by adopting the following strategies:

- Focus on quality rather than quantity.

- Use fresh raw materials and maintain hygienic processing conditions.
- Diversify product lines to cater to different consumer preferences.
- Adopt attractive branding and eco-friendly packaging.
- Participate regularly in entrepreneurship and skill development programmes.
- Utilize digital marketing and e-commerce platforms.
- Form producer groups or cooperatives for collective marketing.
- Maintain proper financial records and inventory management.
- Continuously innovate by introducing new products and flavors.
- Seek guidance from research institutions and extension agencies.

Innovation, quality assurance, and customer satisfaction are the key drivers of long-term business success.

Future Prospects

The future of women entrepreneurship in fisheries value addition is highly promising. Rising consumer awareness regarding nutrition, increasing demand for ready-to-eat and ready-to-cook seafood products, rapid urbanization, and expanding online markets are creating new business opportunities. Emerging technologies such as vacuum packaging, modified atmosphere packaging, high-pressure processing, freeze drying, smart packaging, and seafood traceability systems are improving product quality and market competitiveness. In addition, marine bioactive compounds, functional foods, nutraceuticals, collagen, fish protein hydrolysates, and seaweed-based products represent rapidly growing market segments. The Government of India's emphasis on the Blue Economy, Atmanirbhar Bharat, Start-up India, Digital India, and women-led development provides a strong foundation for expanding women-owned fisheries enterprises. With access to modern technology, financial support, and market linkages, women entrepreneurs can become key contributors to sustainable economic growth and coastal development.

Conclusion

Women entrepreneurship in fisheries value addition is not merely an income-generating activity—it is a powerful instrument for social transformation, economic empowerment, and sustainable development. By converting raw fish into diversified, hygienic, and high-value products, women can significantly enhance household incomes while reducing post-harvest losses and promoting food security. The combination of scientific processing technologies, entrepreneurship development, government support, digital marketing, and collective action through Self-Help Groups has opened new avenues for women across coastal and inland regions. Strengthening women's participation in fisheries value chains will contribute to employment generation, poverty alleviation, nutritional security, and the realization of India's Blue Economy vision. Empowered women entrepreneurs are not only adding value to fish—they are adding value to society, strengthening rural economies, and inspiring future generations to view fisheries as a dynamic and rewarding enterprise. Investing in women is, therefore, an investment in a more resilient, inclusive, and prosperous fisheries sector.

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**SHORT-FORM VIDEO PLATFORMS AS A NEW FRONTIER
FOR AGRICULTURAL KNOWLEDGE SHARING****Sanjith Kumar P* and A Pushpalatha**

Imayam Institute of Agriculture and Technology ,Thuraiyur

*Corresponding Email: sanjith9444509860@gmail.com**Abstract**

The rapid expansion of digital communication technologies has transformed the way agricultural information is created, disseminated and utilized. Among these innovations, short-form video platforms such as YouTube Shorts, Instagram Reels, Facebook Reels, Moj, Josh, ShareChat, and WhatsApp Status have emerged as powerful tools for agricultural knowledge sharing. These platforms enable extension professionals, agricultural universities, research institutions, agripreneurs, progressive farmers, and private organizations to deliver concise, visually engaging and easily understandable information to farming communities. Unlike conventional extension methods that rely on physical interactions, printed literature or lengthy training sessions, short-form videos provide instant access to practical demonstrations, success stories, weather advisories, pest and disease management techniques, market intelligence and innovative farming practices. The popularity of smartphones, affordable internet connectivity, and increasing digital literacy among rural communities have accelerated the adoption of these platforms. Farmers can now learn new technologies, observe field demonstrations, compare farming practices and interact directly with experts without geographical constraints. Moreover, the visual nature of short-form videos reduces literacy barriers, making agricultural knowledge more inclusive and accessible. These platforms also encourage peer-to-peer learning, allowing farmers to share their own innovations, indigenous knowledge, and success stories, thereby strengthening participatory agricultural extension. Despite numerous opportunities, challenges such as misinformation, digital divide, language barriers, content credibility and limited digital skills continue to affect the effectiveness of short-form video-based extension. Addressing these issues through institutional support, content verification, digital capacity building and strategic partnerships can significantly enhance their impact. This article explores the emergence of short-form video platforms in agricultural extension, their role in improving knowledge dissemination, benefits for farmers, challenges and future prospects for creating a more inclusive, efficient, and sustainable agricultural extension system.

Keywords: Digital agriculture, Social media, Knowledge sharing and Rural innovation.**Introduction**

Agriculture is a key sector supporting rural livelihoods and national food security, especially in developing countries like India, where a large population depends directly or indirectly on farming. Timely access to reliable agricultural information is essential for improving productivity, profitability and sustainability. Farmers require knowledge on improved crop technologies, weather information, pest and disease management, market conditions, government schemes, input availability and climate-resilient farming practices. Agricultural extension services have traditionally connected research institutions with farmers by transferring scientific knowledge into practical applications.

Conventional extension methods, including farm visits, demonstrations, training programmes, radio, television and printed materials, have contributed significantly to agricultural development. However, these approaches often face challenges such as limited outreach, shortage of extension personnel, high costs and delays in information delivery. The increasing need for quick and location-specific advisories has encouraged the adoption of digital communication technologies.

The rapid growth of Information and Communication Technologies (ICTs), smartphones, internet services, and social media platforms has transformed agricultural knowledge dissemination. Farmers are now active participants who access, share and create information through digital platforms. Among these technologies, short-form video platforms have emerged as effective tools for agricultural extension by providing concise, visual and easily understandable content.

Platforms such as YouTube Shorts, Instagram Reels, Facebook Reels, Moj, Josh, ShareChat and WhatsApp Status enable farmers to learn practical techniques related to crop production, pest management, irrigation, livestock care and sustainable farming. These videos support visual learning, improve knowledge retention and encourage peer-to-peer knowledge exchange. Although challenges such as misinformation and digital inequality exist, short-form videos have significant potential to complement traditional extension systems and strengthen agricultural knowledge sharing.

Evolution of Agricultural Knowledge Sharing

Agricultural knowledge sharing has undergone a remarkable transformation over the past century. Traditionally, farming knowledge was transmitted orally from one generation to another, with experienced farmers passing on indigenous practices, seasonal wisdom and locally adapted cultivation techniques to younger members of the community. While this informal system helped preserve valuable traditional knowledge, it often lacked access to scientific innovations and modern technologies.

With the establishment of organized agricultural research and extension systems, particularly after the Green Revolution, formal mechanisms for technology dissemination gained prominence. Agricultural universities, research institutes, extension departments, and Krishi Vigyan Kendras (KVKs) became key institutions responsible for transferring improved crop varieties, fertilizer recommendations, irrigation methods, pest management strategies, and mechanization technologies to farmers. Common extension methods included field demonstrations, farmer training programmes, exhibitions, field days, agricultural fairs, radio broadcasts, television programmes, newsletters, and printed extension literature.

Although these approaches significantly contributed to increased agricultural productivity, they were constrained by limitations such as inadequate extension personnel, geographical barriers, high operational costs and delayed dissemination of information. In many regions, a single extension worker was expected to serve thousands of farmers, making personalized advisory services difficult. Furthermore, printed materials often failed to reach illiterate or semi-literate farmers, while radio and television communication offered limited opportunities for interaction and feedback.

The emergence of Information and Communication Technologies (ICTs) marked a turning point in agricultural extension. Mobile phones, internet services, digital advisory platforms, and social media transformed the extension landscape by enabling faster, more interactive, and cost-effective

communication. Farmers could now access weather forecasts, market prices, crop advisories, and expert consultations in real time through digital devices. Within this evolving digital ecosystem, short-form video platforms have emerged as a highly effective medium for agricultural knowledge sharing. Their ability to combine visual demonstrations, concise messaging, local language communication, and instant dissemination has addressed many of the shortcomings of traditional extension approaches. Instead of reading lengthy manuals or attending distant training programmes, farmers can observe practical demonstrations directly on their smartphones, making learning more engaging, understandable, and applicable to real-world farming situations.

Rise of Short-Form Video Platforms in Agriculture

The digital revolution has transformed agricultural knowledge dissemination by introducing new communication tools that improve access, understanding, and farmer participation. Among these innovations, short-form video platforms have emerged as effective tools for agricultural extension by providing concise, visual and easily accessible learning materials. The growth of affordable smartphones, low-cost internet services and increasing rural connectivity has encouraged farmers, rural youth and entrepreneurs to use digital platforms for agricultural learning and communication.

Short-form videos, usually ranging from a few seconds to a few minutes, support microlearning by presenting specific agricultural practices such as seed treatment, pest management, irrigation methods and crop production techniques in a simple format. Platforms like YouTube Shorts, Instagram Reels, Facebook Reels, WhatsApp Status, Moj, Josh, and ShareChat are increasingly used by agricultural institutions, extension agencies, and farmers to share technologies, success stories, and advisories.

These platforms also promote peer-to-peer learning by allowing farmers to create and share their own experiences. Regional language content, subtitles, and visual demonstrations improve accessibility among diverse farming communities. During the COVID-19 pandemic, short-form videos helped maintain agricultural advisory services when traditional extension activities were restricted. With advantages such as speed, accessibility and wider reach, short-form video platforms are becoming important components of modern agricultural extension systems.



Fig.1. The Evolution of Short-Form Video

Farmers Prefer Short Videos for Learning

Farmers increasingly prefer short-form videos for learning because they provide agricultural information in a simple, practical, and engaging format. Unlike lengthy written materials, videos can effectively demonstrate complex practices such as pest management, nutrient application,

irrigation techniques, and improved cultivation methods through visual examples. This makes scientific information easier to understand and apply in real farming situations.

The short duration of these videos suits farmers' busy schedules, allowing them to learn during short breaks without interrupting their daily activities. Visual demonstrations improve knowledge retention by showing tools, techniques and field operations clearly. They are also beneficial for farmers with limited literacy because information can be delivered through local language narration, images and demonstrations.

Farmer-generated videos increase trust by showcasing successful experiences under similar local conditions, encouraging others to adopt new technologies. Interactive features allow farmers to ask questions, share experiences, and communicate with experts, creating a participatory learning environment. The ability to replay and share videos further strengthens knowledge transfer among farming communities.

Short-form videos also motivate rural youth by presenting agriculture as an innovative and entrepreneurial sector. Through convenience, accessibility, peer learning, and practical demonstrations, these platforms have become valuable tools for modern agricultural education and extension.

Major Short-Form Video Platforms Used in Agricultural Extension

Several digital platforms have become valuable channels for agricultural communication. Each platform possesses unique features that cater to different user groups and extension objectives.



Fig.2. Several Digital Platforms

YouTube Shorts

YouTube Shorts has emerged as one of the most influential platforms for agricultural education. Agricultural universities, ICAR institutes, Krishi Vigyan Kendras (KVKs), State Agricultural Universities, NGOs, and agripreneurs regularly publish short instructional videos covering crop production, horticulture, livestock management, fisheries, beekeeping, mushroom cultivation, organic farming and farm mechanization. Its extensive reach and search functionality enable farmers to access reliable agricultural information conveniently.

Instagram Reels

Instagram Reels has become increasingly popular among young farmers, agricultural influencers, and rural entrepreneurs. Creative visual presentation, music integration, captions, and hashtags make agricultural content more attractive and engaging. Topics commonly featured include hydroponics, precision agriculture, urban farming, value addition, agribusiness marketing and innovative farm machinery.

Facebook Reels

Facebook continues to have a substantial rural user base. Agricultural departments, extension agencies, and farmer organizations use Facebook Reels to disseminate seasonal crop advisories, training announcements, success stories, and government schemes. Community groups facilitate knowledge exchange among farmers facing similar production challenges.

WhatsApp Status and Channels

Although primarily a messaging application, WhatsApp has become an essential extension communication tool. Extension officers, scientists, KVKs, and farmer producer organizations circulate short videos through WhatsApp groups, Status updates and Channels. Farmers receive localized weather forecasts, disease alerts, market information, and management recommendations directly on their mobile devices.

Moj, Josh, ShareChat and Other Indian Platforms

Following the rapid growth of indigenous social media applications, several Indian platforms have gained popularity in rural areas. Their support for multiple regional languages makes them particularly useful for agricultural communication. Localized content featuring nearby farming practices, traditional knowledge, and region-specific crop advisories increases user engagement and improves knowledge dissemination.

Table 1. Comparison of Traditional and Short-Form Video-Based Extension

Parameter	Traditional Extension	Short-Form Video Extension
Communication	Face-to-face	Digital
Coverage	Limited	Very High
Cost	High	Low
Speed	Slow	Instant
Interaction	Limited	High
Demonstration	Physical	Visual Digital
Accessibility	Time-bound	Anytime
Language	Limited	Multiple Regional Languages

Benefits of Short-Form Video Platforms for Farmers and Agricultural Extension

The increasing popularity of short-form videos has generated numerous benefits for farmers, extension professionals, researchers, policymakers and agribusiness organizations. These platforms complement conventional extension methods by providing rapid, interactive and cost-effective communication.

Rapid Dissemination of Agricultural Information

One of the greatest advantages of short-form videos is the speed at which information can be disseminated. During pest outbreaks, disease epidemics, weather emergencies, or market fluctuations, extension agencies can immediately publish short advisory videos that reach

thousands of farmers within a few hours. This rapid communication helps farmers make timely management decisions, thereby reducing production losses.

Cost-Effective Extension

Traditional extension programmes require considerable expenditure on travel, demonstrations, training materials and human resources. In contrast, a single educational video uploaded on a digital platform can reach millions of viewers at minimal additional cost. This significantly enhances the efficiency of extension programmes, especially in resource-constrained environments.

Increased Accessibility

Farmers residing in remote villages often have limited access to extension personnel. Short-form video platforms eliminate geographical barriers by delivering agricultural information directly to smartphones. Farmers can learn anytime and anywhere without travelling to training centres.

Visual Demonstration Improves Learning

Agriculture involves numerous practical operations that are easier to understand through visual demonstrations than written descriptions. Short videos clearly illustrate seed treatment, transplanting techniques, fertilizer application, pest identification, pruning methods, irrigation scheduling, grafting, harvesting and post-harvest handling. Visual learning significantly improves comprehension and technology adoption.

Farmer-to-Farmer Learning

Peer learning has always been an important component of agricultural extension. Digital platforms strengthen this process by enabling farmers to share successful innovations with wider audiences. Videos featuring local farmers demonstrating improved technologies often generate greater trust than conventional extension messages because viewers can observe practical results under similar farming conditions.

Promoting Innovation

Short-form videos encourage experimentation and innovation. Farmers frequently upload creative solutions to local agricultural problems, including low-cost machinery, water-saving techniques, indigenous pest management practices and value-added agricultural products. These innovations inspire others to adapt and improve farming practices.

Youth Engagement

The average age of farmers is increasing in many countries. Attracting young people to agriculture has therefore become a major policy priority. Since rural youth are already active users of digital platforms, short-form videos make agriculture more attractive by presenting it as a modern, technology-driven profession. Videos on drone technology, precision farming, hydroponics, protected cultivation, agribusiness startups and digital marketing particularly appeal to younger audiences.

Women's Participation

Short-form videos provide flexible learning opportunities for rural women who may face mobility or time constraints. Videos on kitchen gardening, mushroom cultivation, dairy farming, poultry, food processing, nutrition, handicrafts and entrepreneurship support women's empowerment and income generation.

Strengthening Climate-Smart Agriculture

Climate variability has increased the need for timely advisory services. Digital videos help disseminate information on drought management, flood preparedness, weather-based crop planning, water conservation, integrated farming systems, and climate-resilient crop varieties. Such knowledge strengthens farmers' adaptive capacity.

Strengthening Agricultural Entrepreneurship

Agricultural entrepreneurs use short videos to market products, promote value-added commodities, demonstrate innovative technologies and build customer trust. This contributes to rural employment generation and agricultural commercialization.

Future Prospects of Short-Form Video Platforms in Agricultural Extension

The future of agricultural extension is expected to become increasingly digital, personalized and interactive. Short-form video platforms will play a central role in this transformation by integrating emerging technologies with farmer education. Artificial Intelligence (AI) can recommend personalized agricultural videos based on cropping patterns, geographical location, weather conditions and previous viewing behaviour. Machine learning algorithms may identify farmers' information needs and deliver customized advisory content in real time.

Augmented Reality (AR) and Virtual Reality (VR) technologies may further enhance short-form videos by allowing farmers to visualize crop diseases, machinery operation, irrigation systems or farm layouts interactively. Multilingual automatic translation and voice-over technologies will enable agricultural videos to reach farmers speaking different regional languages without requiring separate video production. Government agencies and research institutions are expected to strengthen partnerships with digital creators, ensuring that scientific recommendations reach wider audiences while maintaining quality and credibility. Future extension programmes are likely to adopt a hybrid model that combines traditional field demonstrations with digital videos, online consultations, mobile advisory services and artificial intelligence-based decision support systems. Such integration will enhance the effectiveness, inclusiveness and sustainability of agricultural extension.



Fig.3. Future Prospects of Short-Form Video Platforms in Agricultural Extension

Table 2. Opportunities and Challenges

Opportunities	Challenges
Wider outreach	Misinformation
Low-cost extension	Digital divide
Interactive learning	Poor internet connectivity
Farmer participation	Algorithm bias
Local language communication	Content verification
Climate advisories	Commercial influence
Entrepreneurship	Privacy concerns
Youth engagement	Low digital literacy

Conclusion

Short-form video platforms have emerged as powerful tools for modern agricultural extension by providing farmers with timely, practical and easily understandable information. They support visual learning, peer-to-peer knowledge sharing, and wider access to scientific agricultural practices. While challenges such as misinformation, digital inequality and content validation remain, effective collaboration among agricultural institutions, extension agencies, and digital creators can enhance their impact. By integrating digital platforms with traditional extension methods, short-form videos can strengthen farmer education, promote climate-smart agriculture, encourage innovation adoption and contribute to sustainable rural development.

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SPECIES DIVERSITY AND IMPORTANCE OF GENUS PETHIA AND PUNTIOUS FROM THE WATER BODIES OF BIHAR, INDIA

Gourav Ranjan Padhi, Roshan Kumar Ram*, Mukesh Kumar Singh, Sanjenbam Bidyasagar Singh and Pravesh Kumar

College of Fisheries, Dholi, Muzaffarpur, 843121,
Dr. Rajendra Prasad Central Agricultural University,
Pusa, Samastipur, 848125, Bihar

*Corresponding Email: roshan.cof@rpcau.ac.in

Abstract

The genera *Puntius* and *Pethia* represent an important component of the freshwater fish diversity of Bihar and contribute significantly to aquatic ecosystem functioning and rural livelihoods. This article compiles available information on the species diversity and importance of these genera based on authenticated literature, standard ichthyological references, and peer reviewed scientific publications. A total of three species of *Puntius* (*P. sophore*, *P. chola*, and *P. terio*) and four species of *Pethia* (*P. ticto*, *P. conchonius*, *P. phutunio* and *P. gelius*) were confirmed from Bihar. Furthermore, records of certain species reported from Bihar were critically evaluated due to the lack of authenticated evidence. The review highlights their ecological roles and trophic interactions, along with their nutritional, ornamental, and livelihood significance. It also identifies major conservation concerns.

Keywords: *Puntius*, *Pethia*, Cyprinidae, Species diversity, Ornamental fish, conservation.

Introduction

Freshwater ecosystems are among the most biologically diverse habitats on Earth and support a rich assemblage of fish fauna that play crucial ecological, economic, and nutritional roles in aquatic environments (Jayaram, 2010; Talwar & Jhingran, 1991). The Indian subcontinent is recognized as one of the major centres of freshwater fish diversity, harbouring a large number of endemic and commercially important species belonging to the family Cyprinidae (Pethiyagoda *et al.*, 2012; Gupta *et al.*, 2018). Within this family, the genera *Pethia* and *Puntius* constitute an important group of small to medium-sized freshwater barbs widely distributed throughout South and Southeast Asia (Pethiyagoda *et al.*, 2012; Kottelat, 2013). Historically, numerous barb species were placed under the genus *Puntius*, which functioned as a broad taxonomic assemblage for several morphologically similar cyprinid fishes (Jayaram, 1991; Pethiyagoda *et al.*, 2012). However, advances in morphological and molecular systematic studies revealed that the traditional genus *Puntius* was polyphyletic and required taxonomic revision (Pethiyagoda *et al.*, 2012; Sudasinghe *et al.*, 2021). Consequently, Pethiyagoda *et al.* (2012) reclassified the South Asian barbs into several distinct genera, including *Pethia*, *Dawkinsia*, *Systomus*, *Haludaria*, and *Puntius*, thereby improving the understanding of their evolutionary relationships and species boundaries (Pethiyagoda *et al.*, 2012; Gupta *et al.*, 2018). The genus *Pethia* and *Puntius* performs various ecological role, apart from that these genera possess considerable economic importance. Several species are valued as ornamental fishes because of their vibrant coloration, peaceful behaviour, and adaptability to aquarium conditions, making them popular in the global aquarium trade (Pethiyagoda *et al.*, 2012). In addition, these fishes serve as a source of animal protein for rural communities and

contribute to subsistence fisheries in many parts of India (Talwar & Jhingran, 1991; Jayaram, 2010). Their sensitivity to habitat degradation and environmental changes also makes them useful biological indicators for assessing freshwater ecosystem health (Gupta *et al.*, 2018).

The state of Bihar is endowed with extensive freshwater resources including the rivers Ganga, Gandak, Kosi, Bagmati, Kamla, Mahananda, Burhi Gandak, numerous oxbow lakes, wetlands, reservoirs, and village ponds that support diverse fish communities (Sarkar *et al.*, 2010). These water bodies provide suitable habitats for several species of *Pethia* and *Puntius*, which form an integral component of the state's indigenous ichthyofauna (Talwar & Jhingran, 1991). Despite their ecological and economic significance, comprehensive information on the diversity, distribution, and importance of these genera in Bihar remains limited and fragmented across various taxonomic and fisheries studies. Assessment of species diversity is essential for understanding community structure, monitoring environmental changes, and developing effective conservation and management strategies (Magurran, 2004). Documentation of *Pethia* and *Puntius* diversity in Bihar is particularly important because freshwater ecosystems are increasingly threatened by habitat modification, pollution, overexploitation, invasive species, and climate-induced alterations in hydrological regimes (Dudgeon *et al.*, 2006). Detailed investigations on these barbs can therefore provide valuable baseline information for biodiversity conservation, sustainable fisheries management, and future taxonomic research.

The present study aims to document the species diversity and evaluate the ecological and economic importance of the genera *Pethia* and *Puntius* occurring in different water bodies of Bihar. The findings are expected to contribute to a better understanding of the ichthyofaunal wealth of the region and support future conservation initiatives for indigenous freshwater fishes.

Diversity and Importance of the Genera *Puntius* and *Pethia* in Bihar

The species of genus *Puntius* are distributed widely across South Asia and exhibit considerable ecological adaptability, allowing them to thrive in both lotic and lentic freshwater habitats (Froese & Pauly, 2016; Kottelat, 2013). In Bihar, species such as *Puntius sophore*, *Puntius chola*, and *Puntius terio* have been reported from different freshwater ecosystems, indicating the successful adaptation of the genus to the varied hydrological conditions of the state. The species of genus *Pethia* are widely distributed in South Asia and are especially abundant in rivers, wetlands, and floodplain ecosystems. In Bihar, species such as *Pethia ticto*, *Pethia conchonius*, *Pethia phutunio* and *Pethia gelius* have been documented from different water bodies, highlighting the considerable diversity of the genus within the state. The occurrence of these species across rivers, floodplain wetlands, and ponds demonstrates their broad ecological adaptability and contributes significantly to the ichthyofaunal diversity of the state (Jayaram, 2010; Sarkar *et al.*, 2010).

Notes on Least Reported Species from Bihar

During the course of reviewing published literature, taxonomic monographs, regional fish faunal reports, and authenticated databases, only a limited number of *Puntius* and *Pethia* species could be reliably confirmed from the freshwater ecosystems of Bihar. However, *Puntius amphibius* (Valenciennes, 1842) and *Pethia guganio* (Hamilton, 1822) have been referred in secondary sources (Few Journals), local checklists and authoritative work like *Freshwater Fishes of the Indian Region* by Jayaram (2010).

Importance of Genera *Puntius* and *Pethia*

Although species comes under genera *Puntius* and *Pethia* regarded as small indigenous freshwater fishes, possess considerable ecological, economic, and conservation significance. These fishes

contribute to the structure and functioning of aquatic ecosystems while simultaneously supporting food security, ornamental fisheries, and livelihood generation (Fig. 1). Owing to their diverse roles in freshwater environments, they are increasingly recognized as valuable biological resources requiring sustainable management and conservation (Thilsted & Wahab, 2014; Chutia *et al.*, 2024).

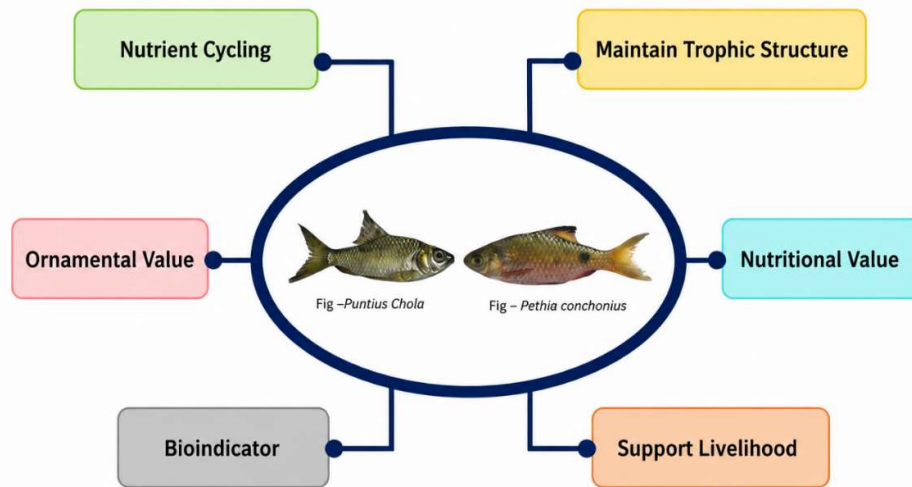


Fig. 1: Importance of genus *Puntius* & *Pethia*

Ecological Importance

Species of *Puntius* and *Pethia* play a significant role in nutrient recycling within freshwater ecosystems through their feeding activities. Most species exhibit omnivorous feeding habits and consume phytoplankton, zooplankton, algae, aquatic insects, detritus, and other organic matter, by processing organic materials and transferring nutrients between trophic levels, these fishes contribute to nutrient cycling and ecosystem productivity (Gupta, 2015; Solo, 2025). Species of both genera occupy intermediate trophic positions in freshwater food webs and function as important links between primary producers and higher consumers (Gupta, 2015). Their feeding behaviour helps regulate populations of planktonic organisms and aquatic invertebrates, thereby contributing to trophic balance and ecosystem stability (Gupta, 2015; Solo, 2025). These fishes also serve as prey for larger predatory fishes, birds, and aquatic reptiles, further strengthening food-web connectivity (Talwar & Jhingran, 1991).

Nutritional Importance

Many species of *Puntius* and *Pethia* are consumed as small indigenous fishes and contribute significantly to rural nutrition and food security. These fishes are rich sources of high-quality protein, essential amino acids, vitamins, calcium, phosphorus, iron, and other micronutrients. Their regular consumption can help alleviate micronutrient deficiencies among rural populations, particularly women and children (Jena *et al.*, 2018; Thilsted & Wahab, 2014).

Table 1: Nutritional Composition of *Puntius sophore* (Pool barb)

(Mahanty *et al.*, 2014; Mohanty *et al.*, 2019; Jena *et al.*, 2018)

Scientific Name	Common Name	Nutritional Composition	
<i>Puntius sophore</i>	Pool barb	Moisture (%)	70.65–75.70
		Crude Protein (%)	14.44-16.30

Scientific Name	Common Name	Nutritional Composition	
		Crude Fat (%)	3.55-16.19
		Total PUFA (% of total fatty acids)	42.86
		EPA + DHA (% of total fatty acids)	9.47
		Calcium (mg kg ⁻¹)	9,748.2
		Potassium (mg kg ⁻¹)	2,283.7
		Iron (mg kg ⁻¹)	115.0
		Zinc (mg kg ⁻¹)	51.1
		Vitamin A (µg kg ⁻¹)	8,613.8
		Vitamin D (µg kg ⁻¹)	4066.6
		Vitamin E (µg kg ⁻¹)	30,685.8
		Vitamin K (µg kg ⁻¹)	8,842.0

Ornamental Importance

The genera *Puntius* and *Pethia* possess considerable ornamental value due to their vibrant colouration, attractive morphology, hardiness, and compatibility with community aquaria. Several species, particularly *Pethia conchonius* (Rosy barb), *Pethia ticto* (Ticto barb) and *Pethia gelius* (Golden barb) are regularly traded in the aquarium industry and contribute significantly to the indigenous ornamental fish sector. Growing consumer preference for native ornamental fishes has further increased their commercial importance and created opportunities for sustainable livelihood generation through ornamental fisheries and aquarium trade activities (Sit *et al.*, 2020; Chutia *et al.*, 2024).

Livelihood Support

Beyond their ecological and nutritional significance, species of *Puntius* and *Pethia* play an important socio-economic role by supporting the livelihoods of local fishing communities and stakeholders involved in the ornamental fish sector. The collection, trade, and culture of these fishes generate supplementary income, especially in rural and wetland-dependent areas, while the expanding demand for indigenous ornamental species offers considerable potential for sustainable livelihood enhancement and small-scale entrepreneurship (Bipinchandra *et al.*, 2025; Sit *et al.*, 2020).

Bioindicator Potential

Species of *Puntius* and *Pethia* are sensitive to changes in habitat quality and environmental conditions (Solo, 2025). Variations in their abundance, distribution, and diversity may indicate alterations in water quality, habitat degradation, and ecosystem disturbances (Sarkar *et al.*, 2010). Therefore, these fishes can serve as useful biological indicators for monitoring freshwater ecosystem health and biodiversity status (Solo, 2025).

Conservation Concerns

Despite the ecological and economic importance of genera *Puntius* and *Pethia*, populations of several species are threatened by habitat degradation, pollution, wetland loss, river modification, and biological invasions (Sarkar *et al.*, 2010). Anthropogenic pressures have led to declines in population abundance and habitat quality in many freshwater ecosystems (Dudgeon *et al.*, 2006). Comprehensive documentation of species diversity, population dynamics, habitat preferences, and conservation status is therefore essential for the sustainable management of these valuable fish resources (Sarkar *et al.*, 2010; Jayaram, 2010).

Conclusion

The present study highlights the diversity and nutritional importance of indigenous small fishes belonging to the genera *Pethia* and *Puntius* occurring in Bihar. These species constitute valuable components of freshwater biodiversity and serve as affordable sources of high-quality protein, essential fatty acids, vitamins, and minerals. Conservation of their natural habitats, sustainable utilization, and promotion of culture practices are essential for maintaining their populations and ensuring food and nutritional security. Further research on their biology, distribution, and nutritional attributes will support effective management and enhance their contribution to fisheries development in the region.

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Official Address :

Peshok Tea Estate
P.O.- Peshok, Dist.- Darjeeling
West Bengal, India
PIN-734312

Contact No : +91 9635231406
email : agriindiatoday@gmail.com

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