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NANOTECHNOLOGY FOR TARGETED GENE DELIVERY IN PLANTS

Kirankumar P. Suthar*, Rajkumar B.K., Mrugesh D. Khunt, Vishwa J Patel, Ridhdhi Goraniya and Preeti R. Parmar

Navsari Agricultural University, Navsari 396450, Gujarat, India
*Corresponding Email: Kiransuthar@nau.in

Introduction

Nanotechnology is the creation of useful/functional materials, devices and systems through control of matter on the nanometer length scale (1-100 nm) and exploitation of novel phenomena and properties (physical, chemical and biological) at that length scale (Feyman, 1960). The nanoparticles (NPs) are used for various purposes from pre-historical times but the term nanotechnology first coined by Richard Feyman in 1959 at the annual meeting of the American Physical Society, Caltech (USA). Material when converted to nanoscale shows increased surface area to volume ratio and altered mechanical, thermal, catalytic, electrical, magnetic as well as optical properties reflecting quantum effect. Due to novel physicochemical properties of nanomaterials, nanotechnology has a wide area of application *i.e.* electronics, medicine, military technology, food industries, cosmetic industries, agriculture sector, etc. In the agriculture sector, nanotechnology could be applied for air/water purification, soil amendment, smart delivery system, precision farming, particle farming, development of nano-fertilizer/pesticide/herbicide, pathogen detection and post-harvest processing, etc.

The transgenic technique with its capability to produce plants with novel foreign genes relies on the availability of tool for precise, rapid, and targeted introduction of DNA into cells. The conventional techniques for gene transfer, *viz*., *Agrobacterium*-mediated transformation, particle bombardment, electroporation, microinjection and polyethylene glycol (PEG) mediated transformation, etc., face the critical challenge of low transformation efficiency, genotype and species dependence, tissue damage, unpredictable gene integration, united gene alterations, time-consuming and labor-intensive plant regeneration protocols. These create space for exploring nanotechnology in gene delivery and genetic manipulation.

Nanotechnology in plant transformation

Nanotechnology is revolutionizing plant biotechnology by providing functionalized nanoparticles (or nanovehicles) that can efficiently deliver genetic cargo, overcoming the significant limitations of traditional methods. These nanoscale carriers are engineered to be coated or encapsulated with the desired genetic material such as DNA (for permanent integration) or RNA (for transient expression or gene editing like CRISPR/Cas9). Nanoparticles (NPs) are characterized by ultrafine particles with diameters less than 100 nm and are well recognized for flexible size, shape, and cargo-binding properties, which enable them to surpass defensive primary cell wall barrier. For the past decades, various forms of nanoparticles have been used for sustained and controlled delivery of the exogenous DNA including carbon carriers (carbon dots, single- and multi-walled carbon nanotubes), metallic carriers (gold nanosphere, gold nanorods, gold nanoclusters, and iron oxide clusters), silicon carriers, and bio-inspired carriers (liposomes, and vesicles) (Cunningham *et al*., 2018).

The true power of this method lies in its ability to facilitate targeted gene delivery through a specific, step-wise mechanism that neutralizes the plant cell's natural defenses. The process begins with the nanoparticle-cargo complex sequentially penetrating formidable plant barriers: first, the cuticle and stomata (if applied to the leaf surface); second, the rigid cell wall (often through passive diffusion due to their small size or physical insertion); and finally, the plasma membrane (typically via endocytosis or direct membrane interaction). Once inside the cell, the complex undergoes intracellular trafficking moving through the cytoplasm and eventually achieving delivery to the final target organelle, which can be the nucleus or the chloroplasts. Successful delivery and expression of the genetic material ultimately lead to transient transformation (temporary expression for research or genome editing) or stable transformation (integration into the host genome for inheritable traits). Thus, Nanoparticles improve gene delivery efficiency and precision by overcoming plant cell wall barriers. Combining nanotechnology with CRISPR/Cas and tissue culture methods can significantly advance plant genetic engineering. Further, Nano-enabled gene delivery can target nuclear, chloroplast, and mitochondrial genomes without causing significant tissue damage, and thus enhance the precision and effectiveness of genetic modifications.

Current Research

The advancements in nanoparticle-mediated gene delivery systems (syringe infiltration, vacuum infiltration, biolistic delivery, magnetofection, ultrasound-based delivery, and spray techniques) have been validated across numerous studies showcasing diverse materials and techniques to overcome cellular barriers and enhance transformation efficiency. The use of ultrasound-mediated delivery was notably explored by Jun *et al*. (2008), who successfully penetrated *Dioscorea zingiberensis* cells. These complexes demonstrated a vital dual role: protecting the DNA from both DNase I cleavage and physical ultrasound damage ultimately achieving nuclear membrane penetration and a transformation frequency exceeding 5%. Similarly, Yu-qin *et al*. (2012) observed high transformation in tobacco cells using ZnS NPs functionalized with positively charged poly-L-lysine (PLL) to deliver GUS-encoding plasmid DNA with an optimal ultrasound condition (60 W for 20 min), yielding an impressive 88.51% regeneration efficiency and 52.67% PCR-positive plants, confirmed by Southern blot.

Beyond ultrasound, engineering the physical properties of carriers has proven essential. Frame *et al*. (2000) demonstrated that simply reducing the size of gold particles used in biolistic bombardment from the routine 1.0 µm to 600 nm significantly increased maize callus transformation efficiency from 1.0% to 14.1%, highlighting the superior penetration capacity and reduced damage of smaller particles. Furthermore, Torney *et al*. (2007) pioneered the use of nanotechnology in intact plant cells showing that mesoporous silica nanoparticles (MSN) could enter tobacco protoplasts *via* endocytosis (7 ± 3%). They enhanced DNA delivery by functionalizing the MSN surface with triethylene glycol (TEG) and achieved successful transformation in intact tobacco cotyledons using a bombardment method with gold-capped MSN, reporting an efficiency of 32 ±11 green fluorescent protein (GFP) events per bombarded cotyledon. This study also proved the MSN's potential for co-delivery of DNA and chemicals using an inducible GFP expression system.

Subsequent work by the same group further refined co-delivery and biolistic enhancement. Martin-Ortigosa *et al*. (2012a) successfully co-delivered both protein (BSA) and DNA (eGFP) into onion epidermal cells using gold-functionalized MSN with microscopic evidence confirming the release of both cargoes within the cell. The group also showed that gold plating could improve the density of MSN thereby boosting their biolistic delivery efficiency, especially when combined with a specific DNA-coating protocol (calcium chloride and spermidine) and the inclusion of 600 nm gold particles (Martin-Ortigosa *et al*., 2012b). This strategy culminated in the successful delivery of Cre recombinase protein loaded within gold-plated MSN into maize embryos resulting in the recombination of *loxP* sites and the successful regeneration of up to 20% of bombarded embryos into fertile plants confirmed by molecular and sequencing analyses (Martin-Ortigosa *et al*., 2013). Complementing these efforts, Liu *et al*. (2009) confirmed the capability of single-walled carbon nanotubes (SWNTs) to effectively penetrate the cell wall and plasma membrane of intact tobacco cells in a time and temperature-dependent manner, validating their use as non-viral DNA carriers. Finally, the potential of calcium phosphate NPs as a novel non-viral gene delivery system was confirmed by Ardekani *et al*. (2014), who achieved and verified stable GFP transformation in tobacco. Carbon nanotubes (CNTs) and carbondots are used to deliver biomolecules, such as DNA, RNA, and proteins, into mature plants for gene expression and silencing. This method is rapid, efficient, and non-damaging for the delivery of DNA and RNA, overcoming the limitations of traditional methods such as the gene gun or agrobacterium-mediated transformation (Demirer *et al*., 2018). Delivery of plasmid DNA into wheat microspores faces many difficulties, mainly due to the presence of the cell wall, which contains several layers that limit gene delivery. This problem can be overcome using rosette nanotubes (RNTs). Plasmid DNA coated with rosette nanotubes was transferred into the wheat microspores under favorable conditions. Wheat Microscope can germinate embryos, leading formation of haploid plants (Cho *et al*., 2020). Molesini *et al*. (2022) used a nanovector to deliver dsRNA into very young tomato flower buds to transfer targeted genes within the plant. Two types of genes are transferred to tomato flower buds, SIIAA9 and STAGL-6 lead to larger ovarian growth without pollination. Recently, Ben-Haim *et al*. (2024) delivered DNA into *Nicotiana bonthamiana* cells by casein nanoparticles with confirmed gene expression.

Advantages:

1. **Increased efficiency:** The nanoparticle-mediated gene delivery demonstrates the potential of nanoparticles in overcoming barriers such as the plant cell wall and enhancing the uptake of genetic material.
2. **Species compatibility:** Nanoparticles can overcome the species-dependency limitations**.**
3. **Versatility:** The versatility of nanoparticles allows for enhanced compatibility with a wide range of plant species. They are effective for delivering a wide range of genetic cargos, including DNA, RNA, and proteins.
4. **Integration with gene editing:** Nanotechnology can be combined with genome editing tools like CRISPR/Cas for more precise genetic modifications.

Challenges

The utilization of nanoparticles as carriers for delivering biomolecules into diverse plant species raises potential ethical and regulatory concerns, as nanoparticles may inadvertently pose environmental risks through accumulation in soil and water, as well as in edible plant tissues; therefore, comprehensive risk and safety assessments are necessary. Moreover, an in-depth investigation is essential to properly elucidate the interaction between nanoparticles and the ecosystem. Furthermore, various nanoparticles have demonstrated antibacterial properties against bacterial species; consequently, the accumulation of these nanoparticles in soil or water will significantly affect the bacteria essential for the normal growth and development of plants.

Conclusion

Nanotechnology has emerged as a powerful and versatile paradigm for modern plant genetic engineering, effectively overcomming the critical challenges of low efficiency and genotype dependency inherent in conventional transformation methods. Functionalized nanoparticles (NPs), such as carbon nanotubes, mesoporous silica nanoparticles (MSN), and metallic NPs, act as superior, protective carriers, demonstrating remarkable success in penetrating all four major plant barriers: the cuticle/stomata, cell wall, and plasma membrane. The collective evidence from research highlights the technical superiority of these nanovehicles: they protect genetic cargo (DNA/RNA) from degradation agents like DNase I and physical stress like ultrasound, enable co-delivery of multiple cargoes (DNA and protein/chemical), and allow for the temporal and spatial expression of desirable traits. Moreover, strategic modifications including surface functionalization (e.g., TEG, PLL, gold plating) and optimizing delivery parameters (e.g., particle size in biolistics) have significantly boosted transformation efficiencies in various studies. Nanotechnology is a promising tool to accelerate the precise and rapid development of genetically enhanced crops, making it indispensable for future advancements in agricultural biotechnology. Future research should optimize nanocarriers for efficient and precise gene delivery while minimizing off-target effects and must also address the potential toxicity and ensure the nanoparticles can be rapidly degraded and excreted from the plant after their function is complete.

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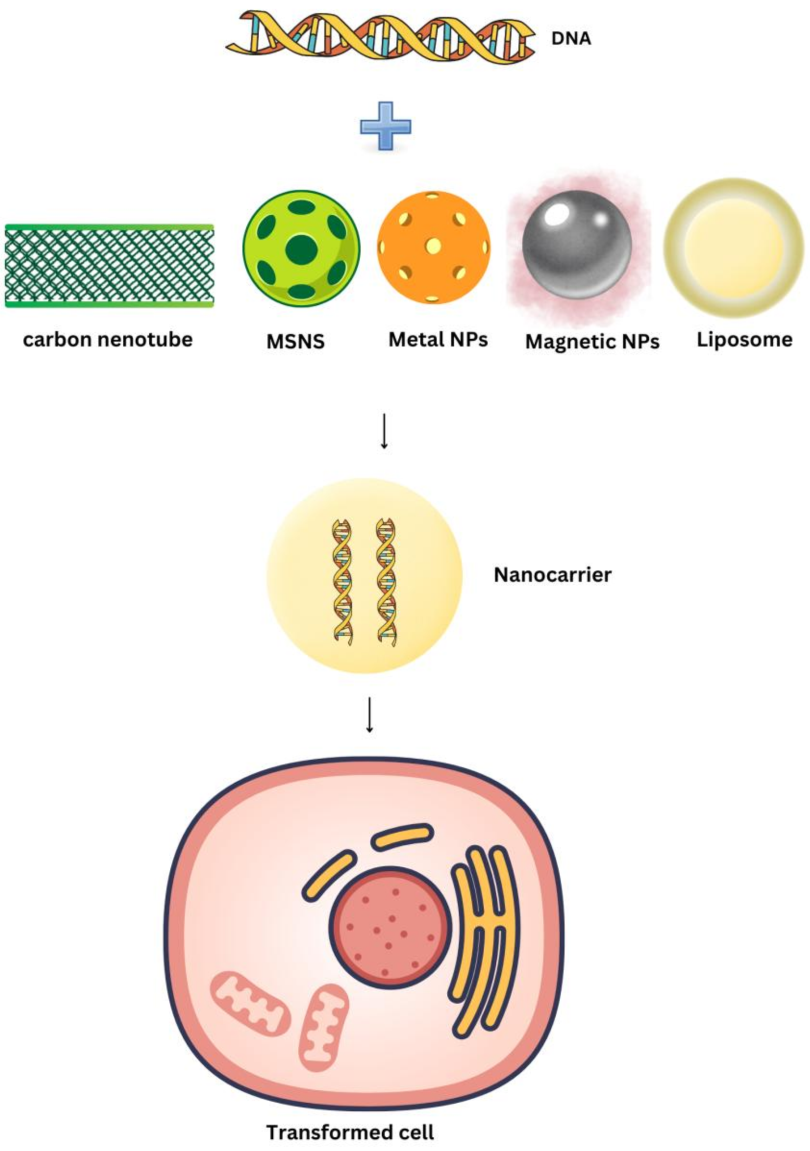

Overview of Nanotechnology for targeted gene delivery in plants

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MICROGREENS: THE NEW GENERATION SUPER FOOD

Soumendar Nath Das
Lecturer in Horticulture, Susrijo Institute of Agricultural Science, Technology and Management, Kalyani, Nadia, West Bengal- 741235.
Corresponding Email: somudas1963@gmail.com

Microgreens are new generation potent food whose popularity is increasing among the city dwellers with time. Microgreens are tiny and young edible green plants consisting roots, stem and to embryonic leaves. They are concentrated in nutrients like vitamins, minerals, antioxidants and many bioactive compounds which making them a potent superfood. They have found more nutritious than their mature counterparts. These microgreens not only enhance the aesthetic appeal of meals but also contribute significantly to their nutritional content.

- **What is microgreens :** When the cotyledonous or embryonic leaves have fully developed and first true leaves have emerged the plant becomes a microgreen. Microgreens are tiny and young edible green seedlings of vegetable and herbs which are harvested within a very short period of time 7-14 days) after seed germination when first pair of true leaves are emerging. The size of the microgreens is ranging from 2.5 to 7.5 cm. They have three major parts comprising a central stem, two cotyledonous leaves and typically one pair of first young true leaves. Microgreens are packed with nutrition and intense flavour imitating their mature counterparts.
- **Microgreen crops :** There are so many varieties of plants which can be grown as microgreens including lettuce, red cabbage, popcorn, spinach, carrot, radish, beetroot, amaranth, pea, celery, broccoli, turnip, coriander, parsley, basil, wheat, mustard, kale etc.
- **Importance :** Many urban people reside in the cities where they do not have ready access to the availability of fresh agricultural products like fruits and vegetables resulting in lack of complete package of essential nutrients. They have to depend mainly on processed and packaged foods. Non-availability of fresh and pesticide toxicity free vegetables and fruits for daily consumption is becoming a big problem. The urban people have to depend on distant rural areas for their food which limits the availability of produce that has shorter shelf life and poor transport ability. The vast demand for this functional food has been created throughout the world due to increased health consciousness associated with changing lifestyle. Microgreens are considered practical nourishments which are food items that have explicit wellbeing advancing and infection forestalling properties that to their typical health benefits. These are additionally named asadecent wellspring of minerals in the human eating regimen. They are an arising class that can tackle practically all the medical conditions identified with wholesome lack. The culinary value of microgreens rose high in the past decade due to its high nutritional status, versatility, flovour profile and crispiness nature imparted to the dish.
- **Uses:** Microgreens first made their appearance as a garnish in the early 80 s but soon caught up as the healthiest trend due to their nutritional superpowers. In India microgreens however are still at the outset of becoming a part of our daily diet. The fine-dine restaurants in major metro cities like Delhi, Kolkata, Mumbai and Bengaluru have recently started adding microgreens to their food items like salad, sandwiches, warm

dishes, appetizers, desserts, garnishes, soup and sauces, juices and tails. Microgreens can be consumed raw in salads to get the chance of the highest possible nutritional intake. They can also be cooked, garnished on soups added in sandwiches, burgers or smoothies or used as toppings. They can be added to soups and sauces for added flavour and texture. Microgreens can be used in rice dishes also. They can be added to stirfries, omlets and other warm dishes for providing a fresh and crunchy element. Microgreens are a popular garnish for soups, pizzas, pastas and other dishes for adding a pop of colour and flovour. They can be used as an ingredient in sandwiches and wraps to add a fresh and vibrant element.

- **Nutritional Benefits :** Microgreens possess a high nutritional status, offering concentrated vitamins, minerals, fibers, antioxidants and other bioactive compounds. They are higher in nutritional content than those of mature plants. The key nutrients includes vitamins A, B, E and K, alongside minerals like potassium, magnesium, calcium, iron and zinc. Their rich profile of phytochemicals such as phenolic compounds and carotenoids contribute to significant health benefits, including anti-inflammatory, anticancer and immune boosting properties. The nutritional composition of microgreens differs according to the types of microgreens, growing medium, amount of sunlight and temperature received and time of harvest. The bright coloured microgreens are found to be more rich in respect of nutrient content than the light ones. Most of the microgreens are low in calories and fat.
- **Health Benefits :** Eating of microgreens lowers the risk of many diseases as that are packed with high amount of vitamins, minerals, antioxidants and different phytochemicals.
  - Microgreens are being the powerhouse of different antioxidants help us to protect cell damage caused by the free radicles.
  - Polyphenols are linked to lower the risk of heart disease and triglyceride and bad LDL cholesterol levels.
  - Microgreens are antioxidant rich food which help to lower the risk of Alzheimer's disease.
  - Being rich in fiber microgreens aid digestion and promote gut health.
  - Microgreens are rich sources of vitamin A, C & E which help to build up strong immune system that helps our body to fight against illness and infection.
  - Polyphenol rich microgreens may lower the risk of various types of cancer.
  - Microgreens may support brain function and improve memory.
  - Antioxidant rich microgreens may help to reduce the type of stress that can prevent sugar from properly entering the cells.
  - Beta carotene found in many microgreens is essential for maintain healthy vision and preventing eye related disorders.
  - Sulphur containing compound like sulforaphane found in broccoli microgreens have been shown to have anticancer properties. They help in detoxifying the body and preventing the growth of cancer cells.
- **Why Microgreens :** Microgreens are nutrient rich food as packed with vitamins, minerals, antioxidants and other bioactive compounds. They have a higher concentration of

nutrients than mature vegetables and herbs. Some varieties of microgreens having up to 40 times more nutrition than grown vegetables.

- Though microgreens are tiny, the concentration of flovour make them a favorite of chefs and food lover people around the world.
- Microgreens can be harvested within a very short period of time making then a quick source of fresh produce. They get ready to eat in just tow weeks.
- They can be grown in rooms, indoor, or in small place which is ideal for urban farming.
- Microgreens farming can be a profitable business with relatively low initial investment or low startup cost.
- Ever increasing of microgreen in domestic demand of microgreens in domistic as well as international markets.
- In creasing demand due to its use in caffe, restaurant, hotels supershops and online market places.
- No question of crop failure as seen in field crops which are grown under outdoor conditions.
- Microgreens can be grown successfully in vertical farming.
- Organic cultivation of microgreens can be a better option.

How to Grow Microgreen :

1. **Selection of seeds:** Microgreens can be grown from selected seeds of variety irrespective of crops like radish, cabbage, beetroot, broccoli, wheat etc. according to season of growth.
2. **Growing container :** Plastic made tray having 4-5 inches depth should be selected.
3. **Growing medium :** Microgreens can be grown in different media like soil and a mixture of cocopeat, vermiculite and perlite @ 5:2:1 ratio respectively. This growing media an releases various plant food elements (macro and micronutrients) very slowly and it can be reused several times for growing microgreens. Medium should be sterilize properly exposed to sunlight.
4. **Sowing of seeds :** Microgreen seeds generally do not require extra natrition for seed germination but needs only ideal conditions (hight, temperature, hunidity and moisture). Seeds can be sown round the year as per consumer's requirement. Seeds should be evenly spreaded over the growing medium and lightly to be covered with a thin layer of medium.
5. **Environment:** For proper seed germination and subsequent growth of the microgreens high light intensity, low humidity, favourable temperature and good air circulation is needed. Seeds can be kept in a warm and dark place for a few days for promoting seed germination.
6. **Watering :** Water is needed for the microgreens. The growing medium should be kept just most by spraying water twice a day with a hard sprayer. Over watering should be avoided.

- **Where to grow** : Microgreens can be grown both indoors and outdoors. Outdoor setups have their own pros and cons . One advantage of growing microgreens outdoor is that it dose not require any artificial light, but outdoor farming needs appropriate environmental conditions. There are many drawbacks of growing microgreens outdoor. There is also the chances of threat of extreme temperature fluctuation and frost. A greenhouse can be a better option for outdoor cultivation of microgreens, but it will be very expensive for the growers. Places like roof tops, balconies, porches, backyards, home kitchens, varandahs, window sills, small rooms and vertical racks and shelves can be used for growing microgreens under indoor conditions. Use of hydroponics and vertical farming may be done for efficient and year round production. Microgreens are gaining popularity due to their high nutritional profiles, rich phytochemical content and intense flavour.

- **Harvesting :** Microgreens are cut along with the stem and attached seed leaves with the help of a pre-sterilized sharp scissor. They are different from the sprouts in the sense that sprouts are only the germinated seeds which are consumed with the embryonic roots and the seeds. If they are left for a longer time, they will begin to elongate faster and lose color and flovour.

  Microgreens can be harvested at 7-14 days after seed germination once the plants are 2-3 inches in height are ready for harvesting. When the cotyledonous leaves have fully developed and first leaves have emerged, the plant becomes a microgreen. In cold weather during winter microgreens take more time (14-28 days) for harvesting depending on the type crop and environmental conditions. Microgreens are cut with sharp scissor or knife just above the roots holding them vertically. After harvest they are kept in clean plastic container.

- **Washing:** The harvested microgreens are thoroughly washed with clean cold running water before use. Dry them after washing and store in a paper warp in the refrigerator. After washing the fresh microgreens can also be consumed to get their nutrition in a fullest way.

- **Packaging :**
  - 100% compostable microgreen packaging container may be perfect option for ecofriendly business.
  - Resealable bags are a popular choice for packing microgreens because they are very convenient and easy to use.
  - Paper Bags lived in plastic with a see through window (baker's bags) can also be used for used for packaging microgreens.
  - Plastic made poly bags can commonly be used.
  - Biodegradable plastic clamshell containers are also available in the market.

- **Storage :** For proper stornge of microgreens they should be kept dry, wrap in a dry paper towel and placed then in a loosely covered container or bag inside the refrigerator. Dry paper towel will absorb the excess moisture. The temperature of the refrigerator will be kept consistent at 10^0-40^0 c , away from direct light for 7-14 days depending on type of microgreen plant. Following precantion should be taken during storing of microgreens.
  - As microgreens are delicate and can bruise easily they should be handled carefully.
  - Excess moisture remaining on microgreens surface should be gently dabbed with a dry paper towel as the excess moisture can promote mold infection and spoilage.
  - Washing of microgreens before storage to prevent premature wilting and decay from excess moisture.

- **Marketing :**
  - Microgreen growers can market their produce to health conscious consumers who are looking for food options directly through online platforms like Big Basket, Flipkart, Blinkit, Amazon farmers market and subscription services.

- Selling of microgreens to hotels, restaurants, caterers, chefs and cafes can be done who are using them for garnishes, flavour and presentation.
- Local buyers who are looking for fresh farm products may be connected directly for selling of microgreens produced.
- Delivery services directly to homes within the local community may be an alternative choice.
- Microgreen growers can place their produce to organic grocery stores and small food stores where customer seek nutrition and ready to eat foods stores where customers seek nutrition and ready to eat foods.
- A professional and memorable brand with a unique logo is to be created and consistent messaging for the material is to be done.
- To encourage larger orders wholesale pricing is to be provided.
- Microgreens can be sold to the companies who are incorporating them into new products.
- Growing microgreens has strong business prospects due to increasing health and wellness trends, offering a high-profit potential with low startup costs and faster growth cycles.

- **Challenges** :
  - As microgreens are grown in indoor condition there may be the chance of disease appearance that can cause the harm to them resulting in unfit for human consumption.
  - As they are perishable due to high moisture content, so their proper packaging and storage is crucial.
  - As the microgreens have a short time span of usability need better strategies for their storage and transport.
  - Damping-off fungal disease can be harmful to the seedlings soon after emergence leading to their premature death.
  - Uneven seed germination and growth of the microgreen seedlings are caused to poor seed quality, lack of moisture and uneven light availability.
  - Microgreens become yellowish or weak if they do not get enough light.
  - Microgreens are cut along with the stem and attached seed leaves with the help of a pre-sterilized sharp scissor. They are different from the sprouts in the sense that sprouts are only the germinated seeds which are consumed with the embryonic roots and the seeds. If they are left for a longer time, they will begin to elongate faster and lose color and flovour.




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STRENGTHENING RESEARCH OUTCOMES THROUGH EXTENSION TO END-USERS LINKAGE: A TRIANGULAR APPROACH TO ACCELERATED AGRICULTURE

Adamu D.A* and Orimafo P.K.

Research Outreach Department,
Nigerian Stored Products Research Institute Ilorin, Nigeria
*Corresponding Email: adamu.davida@gmail.com

Abstracts

In many developing countries, agricultural innovation generated by research institutions seldom reaches end-users in a timely or relevant manner, limiting the potential for productivity gains and rural livelihoods improvement. A key bottleneck is the weak or unidirectional linkage between researchers, extension agents, and end-users. This article argues for a triangular linkage model in which these three actors engage in two-way communication, joint experimentation, co-learning, and continuous feedback loops. The model seeks to bridge the divide between supply-driven research and demand-driven adoption. The article first reviews existing linkage frameworks and critiques their limitations in practice. It then frames the problem of ineffective adoption as a symptom of broken or shallow linkages. The general objective is to strengthen agricultural research by reinforcing connections with extension and end-users using a triangular approach. Specific objectives include diagnosing linkage constraints, piloting institutional mechanisms (e.g. liaison committees, joint trials), assessing impacts on adoption and relevance, and recommending sustainable policy reforms. The justification rests on enhancing research relevance, improving resource efficiency, supporting dynamic learning, fostering institutionalization, scaling impact, and promoting equity. Strengthening the triangular linkage holds promise for accelerating agricultural transformation by narrowing the gap between research outputs and grassroots adoption.

Introduction

Agriculture remains a backbone of many economies in sub-Saharan Africa, Asia, and other developing regions, supplying food, employment, and raw materials. Yet despite decades of investment in agricultural research, many innovations fail to reach or be adopted by farmers, thereby limiting productivity gains. The “last mile” problem where research outputs do not translate into field-level impact often stems from weak linkages between research institutions, extension agencies, and farming communities (end-users). In response, the triangular linkage model (or research–extension–end users’ linkage) has been proposed to reinforce two-way flows of information, feedback, and co-creation of technology. By treating farmers not merely as passive recipients, but as active partners in problem identification, adaptation, and evaluation, the model holds promise for accelerating agricultural transformation. This article discusses the background, problem statement, objectives, and justification of using a triangular approach to strengthen research–extension–end users’ linkages in agriculture.

Background to the study

Research–Extension Linkage in Agriculture The concept of linkage in agricultural systems refers to the communication, coordination, and collaboration among organizations that share a common goal in this case, improving agricultural productivity and livelihoods (Havelock 1986; as cited in

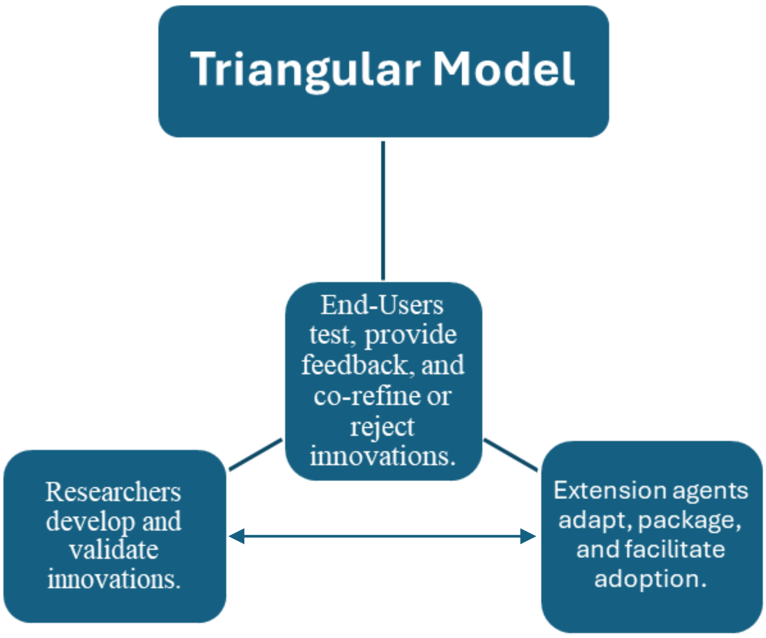
Agbamu 2000). Research–extension linkage has been widely studied as a critical pathway for technology transfer and adoption (Agbamu 2000; FAO 2010). In formal systems, research institutions generate knowledge and technologies, extension services act as intermediaries to package and disseminate them, and end-users adopt, adapt, or reject them. But for that chain to function robustly, communication must flow both downward (from research to end-users) and upward (feedback from end-users to researchers). Weak or broken links lead to irrelevance of technologies, low adoption, and wasted resources.

Gap in Linking to End Users (Farmers)

Although research–extension linkages are well understood in theory, in practice many systems remain linear and top-down. According to FAO, many extension or research organizations still underappreciate the role of farmers (end users) and their organizations in setting priorities and evaluating outcomes (FAO, "Strengthening Research-Extension-Farmer Linkages"). Empirical studies corroborate that extension agents perceive stronger linkages with researchers than with farmers, suggesting an imbalance in communication flows (e.g. in Edo State, Nigeria) (Okoedo-Okojie & Okon 2013). Moreover, in many developing countries, research is designed in isolation from the contextual constraints that farmers face (e.g., labor, capital, risk, local soil & climate), resulting in low adoption. Reviews in Ethiopia, for example, highlight that although linkages are recognized as important, in practice coordination remains weak.

The Triangular Model ("Technology Triangle")

To overcome the limitations of linear models, a triangular or "technology triangle" model has been advanced, emphasizing the interdependence and interaction among researchers, extension agents, and farmers/end users. In this framing:



Olowu & Windapo (1995) and Agbamu (2000) note that none of the three actors can function effectively alone; rather, their interface must be managed through intentional linkage mechanisms.

This triangular interaction harmonizes supply-driven and demand-driven approaches, enhancing relevance, adoption, and scaling of agricultural innovations. Experiences in Strengthening Triangular Linkages Across many countries, attempts to strengthen triangular links have taken different forms: participatory technology development, on-farm trials, liaison committees, joint evaluations, and farmer research committees.

In Nigeria, efforts to integrate research, extension and education (i.e., REE linkage) Nepali, et al., (2020) have been proposed to restructure institutions around community-level centers and land-grant type partnerships to improve service delivery. But these efforts often face institutional, financial, and governance constraints. The need remains for systematic frameworks to understand, diagnose, and strengthen the triangular model in diverse socio-ecological and institutional contexts.

Problem Statement

Despite significant investments in agricultural research and extension, many innovations fail to reach or be adopted by end-users, particularly in resource-constrained settings. The root cause is often a weak, unidirectional, or poorly managed linkage among researchers, extension agents, and farmers (end users). The consequences include: technologies that are poorly adapted to local conditions and farmer constraints, low adoption rates, wasted research investment, and slow agricultural productivity growth, weak feedback loops, whereby farmers' real-world challenges are not communicated back into research agendas. A mismatch between the priorities of researchers and the real needs of end users. Hence, there is a critical need to strengthen and institutionalize the triangular research–extension–end users' linkage in a way that is responsive, inclusive, and sustainable, thereby accelerating agricultural transformation. Therefore, this study considered the following objectives is to: strengthen agricultural research through enhanced linkage with extension services and end users using a triangular model, thereby accelerating adoption and impact of innovations.

Justification

Why invest in strengthening the triangular linkage approach? Several justifications apply: Increased Relevance and Adoption Innovations generated close to farmer realities and with farmer participation are more likely to be relevant and adopted. Triangular linkage ensures that the "voice" of end users shapes research priorities and validation (FAO linkage concept; Agbamu 2000).

Way forward to strengthen triangular linkage approach

Here are some key valuables to consider

- Efficient Use of Research Resources Feedback from extension and farmers helps avoid redundancies, failures, or mismatches in research, thus allocating resources more effectively.
- Dynamic Feedback and Learning A vibrant triangular interface fosters continuous learning, adaptation, and refinement of technologies in real contexts, rather than static top-down transfer.
- Institutional Sustainability Embedding linkage mechanisms in institutional routines (committees, staff exchange, shared budgets) increases resilience and continuity beyond project lifecycles.

- Scaling and Impact With stronger linkages, innovations can be taken to scale more rapidly, with endorsement and advocacy by farmers themselves, thus accelerating agricultural change and meeting food security goals.
- Equity and Inclusiveness Triangular linkages can give marginalized farmers (women, youth, low-income) a seat at the table, promoting inclusive innovation design and dissemination.
- Policy Relevance Results from linked and demand-driven research are more likely to inform policy and extension systems, bridging the gap between science and practice. Given these rationales, strengthening the triangular linkage is not merely desirable but essential to closing the gap between research outputs and agricultural impact.

Conclusion

The triangular linkage approach connecting research, extension, and end users is a promising pathway for accelerating agricultural transformation in developing contexts. However, the mere idea is insufficient; practical mechanisms, institutional reforms, capacity-building, and sustained commitment are needed to operationalize and embed it. Future efforts should focus on context-specific diagnostics, pilot linkage models, impact assessment, and scaling pathways. With such a strategy, the persistent divide between knowledge generation and grassroots adoption can be narrowed, and the promise of agricultural research more fully realized.

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EMERGING APPLICATION OF FRESHNESS INDICATORS IN FOOD PACKAGING: AN OVERVIEW

Aditi Sharma[1*], Akash Deep Shukla[2], Sweta Rai[2], Aman Pal[1], Mohd Abbas[1] and Shivani Jangde[1]

[1]Department of Post-Harvest Process and Food Engineering,
College of Technology, GBPUAT Pantnagar, Uttarakhand, India.
[2]Department of Food Science and Technology,
College of Agriculture, GBPUAT Pantnagar, Uttarakhand, India.
*Corresponding Email: aditisharmangr@gmail.com

Abstract

The limitations of traditional date labels contribute to the ongoing waste and safety issues in the global food system. Intelligent packaging, especially when paired with Freshness Indicators (FIs), represents a shift in food preservation from passive protection to active monitoring and communication. Freshness indicators are labels that can either make contact or remain non-contact and are part of food packaging. They provide visual, digital, or real-time information about the product's quality, spoilage status, and overall history. This extensive review paper critically examines the main concepts, material science, and uses of modern freshness indicators, categorizing them into three types: data carrier systems, pH-responsive (including natural pigments), and chemical chromogenic. It thoroughly covers the key molecular mechanisms, the importance of matching activation energy in Time-Temperature Indicators (TTIs), and the growing role of nanomaterials and the Internet of Things (IoT) in digitizing freshness tracking. The paper concludes that FIs are crucial tools poised to transform the efficiency, safety, and sustainability of the food supply chain in the next ten years. It also highlights key obstacles to commercialization, such as cost-effectiveness, regulatory compliance (FDA and EFSA guidelines on migration), and the need for consumer education.

Keywords: pH-Responsive Dyes, Freshness Indicators (FIs), Time-Temperature Indicators (TTIs), Intelligent Packaging etc.

The global need for smarter food packaging: Introduction

The problem of food loss and waste is one of the biggest sustainability challenges faced worldwide. Globally, around one-third of overall food prepared for people to eat is wasted each year. In 2022, this was about 1.05 billion tonnes (UNEP, 2024). This waste brings a huge economic cost, exceeding $1 trillion each year. It also has a major environmental impact, significantly increasing greenhouse gas emissions. A major reason for this unnecessary waste is the dependence on generic "Best Before" or "Use By" dates especially in developed countries (Eurostat, 2025). These labels are fixed estimates, which means they assume the food has been stored perfectly since it was made. In reality, a package of chicken or a carton of milk may go through temperature changes during transport, storage, or even on the way home from the store. Since the labels do not consider these temperature issues, consumers often throw away food too early out of caution, even if the product is still safe and fresh. The need for real-time, dynamic quality assessment is not just an industry issue. It is a global necessity for food security, economic efficiency, and environmental protection.

Food packaging has evolved through several stages. The traditional role is to contain the product and act as a physical barrier against external threats such as moisture, oxygen O_2, and contaminants also known as passive packaging (Ma *et al*., 2020). Nowadays, a more sophisticated system uses materials in the package to actively change the internal environment. This includes adding oxygen scavengers or antimicrobial agents to extend shelf life referred as active packaging (Kuswandi & Jumina, 2020). Moreover, advanced packaging systems are made to sense, detect, and share information about the condition of the food or its surroundings known as intelligent packaging. Instead of changing the food itself, intelligent packaging informs us about what is happening inside the package (Sohail *et al*., 2018).

Freshness Indicators (FIs) are the important types of intelligent packaging systems. They act as labels or tags that convert complex biochemical changes, such as spoilage, into a simple and easy-to-read signal. This signal is usually a color change or a digital reading. The commercial viability of FIs is strong. The global Freshness Indicator Packaging market was valued at about $1.8 billion in 2024. It is expected to reach $6.7 billion by 2033, growing at an impressive 15.2% CAGR (Marketintelo, 2033). This growth is fueled by Consumer Confidence**,** Supply Chain Optimization and Regulatory Push. FIs offer transparency and peace of mind regarding food quality. Retailers and distributors can use FIs to focus on selling products that are nearing spoilage. They can implement a "First Expired, First Out" (FEFO) policy based on actual freshness instead of fixed production dates. Increasing government attention on cutting food waste and enhancing food safety standards is driving innovation and adoption.

Chemical and pH Responsive Freshness Indicators: The Visible Revolution

Colorimetric freshness indicators are the most user-friendly freshness indicators because they offer a clear, instant visual signal: a change in color that indicates spoilage. They work by detecting the volatile compounds released when food goes bad. The spoilage of protein-rich foods, especially meat, poultry, and seafood, mainly results from microbial action. Bacteria break down proteins and amino acids, producing alkaline volatile compounds known as Total Volatile Basic Nitrogen (TVB-N). These compounds include ammonia and trimethylamine (TMA), which is responsible for the strong, "fishy" smell. This is based on the **p**rinciple of change in pH. TVB-N indicators use pH-sensitive dyes. These compounds change their chemical structure and visible color based on the acidity or alkalinity of the environment. When protein foods spoil, the concentration of volatile amines (TVB-N) increases in the package headspace. These bases dissolve into the indicator material, which raises its pH. The immobilized dye changes color in response to the pH shift. For example, an indicator may appear red in acidic conditions but turn purple or blue when it becomes alkaline and spoiled, as volatile amines build up. This gives a semi-quantitative reading. Intermediate colors may suggest "secondary freshness" or indicate that the product should be used soon (Kuswandi & Nurfawaidi, 2017; Yang *et al*., 2023).

Gas indicators are important for monitoring products that are packaged in a Modified Atmosphere Packaging (MAP) environment. Such as: Carbon Dioxide CO_2 Indicators are used in Products like fresh meat, fresh-cut vegetables, or even kimchi (fermented cabbage), as they continue to respire and spoil inside the package. This metabolic activity and microbial growth generate CO_2. CO_2 dissolves into the aqueous layer of the indicator, forming carbonic acid (H_2CO_3). This causes a decrease in pH (an increase in acidity). CO_2 indicators monitor both microbial activity and freshness loss in MAP products (Baek *et al*., 2020). While Oxygen (O_2) Indicators are important for packages that are meant to be anaerobic, such as vacuum-sealed or MAP packages that are designed to keep out O2 to stop oxidation. They usually include a redox dye, like Methylene Blue, and a reducing agent. Without oxygen, the dye gets chemically reduced and stays colorless. If the package seal breaks and oxygen enters, the dye quickly oxidizes back to its colored form. This gives an immediate warning of package failure, which is an important food safety feature (Shao *et al*., 2021).

Volatile Organic Compound Sensors (VOCs) are a variety of secondary metabolites, such as ethanol, aldehydes, and sulfur compounds. These are produced when carbohydrates and fats break down. Such as: Ethanol is useful for products where fermentation is a major spoilage issue, such as fruit juices, baked goods, or high-sugar fresh produce. Specific sensors use enzymes like alcohol oxidase to detect ethanol concentration and convert it into a signal (Shao *et al*., 2021). Also, Sulfur Compounds are highly smelly products, like durian fruit, release certain sulfur compounds as they ripen or spoil. Indicators can be designed with specific dye combinations to react to these unique VOCs. This allows tracking ripeness (Niponsak *et al*., 2020).

The Natural Trend: Sensitive Dyes and Green Chemistry

While synthetic chemical dyes provide predictable color changes, their use raises significant regulatory and consumer concerns about the dyes moving into food, which is a migration risk. This has led to a major scientific shift toward using safe, natural pigments in food ingredients. Natural pigments are preferred for **s**afety, as many natural pigments come from edible sources like fruits and vegetables. They already have Generally Recognized as Safe (GRAS) status. This simplifies the regulatory approval process (Shao *et al*., 2021). Also, many natural pigments not only change color but also contain helpful antioxidant and antimicrobial properties. This gives the packaging two functions for monitoring and preservation.

The most successful class of natural pH-indicators is the Anthocyanins (ACNs)**.** It is found in high concentration in purple cabbage, black rice, grape skins, and various berries. They are responsible for the red, purple, and blue colors in nature. ACNs act like tiny molecular switches. Their structure changes dramatically based on pH. In acidic conditions (fresh food), the molecule exists as a Flavylium Cation, resulting in a vibrant red color. As food spoils, volatile amines (TVB-N) are released, making the package headspace alkaline (higher pH). The ACN molecule deprotonates, shifting its form to the Quinonoidal Base and then to the anionic Form, causing a color shift through purple and eventually to blue, green, or yellow. Red (Fresh, pH<3) ⇌ Purple (Intermediate) ⇌ Blue/Green (Spoiled, pH.7) (Roy & Rhim, 2020; Liu *et al*., 2024). A major hurdle is that ACNs are sensitive to light, heat, and O2, which can cause them to fade early. Researchers are addressing this issue by encapsulating the ACNs in stable polymer matrices, such as chitosan or nanocellulose (Moradi *et al*., 2019).

Curcumin is extracted from turmeric; Curcumin is another effective pH indicator. It naturally shows a clear color change from yellow (acidic/neutral) to red or brown (alkaline). This makes it suitable for tracking the alkaline shift in degrading proteins (Liu *et al*., 2024). Betacyanins are pigments that give beets and dragon fruit their deep red color, and they respond to pH changes. However, they usually have lower stability and sensitivity compared to ACNs, which limits their common use (Oliveira Filho *et al*., 2022).

The Future of Dynamic Tracking: Data Carrier and Electronic Indicators

While color change is easy for consumers, modern supply chains need data. Data carriers and electronic indicators are advanced tools that record, store, and send accurate information. They connect packaging to digital logistics systems. Time-Temperature Indicators (TTIs) are currently the most commercially developed intelligent packaging technology. They are irreversible devices that track the complete thermal history of a product. This gives a better measure of the remaining shelf life than a fixed date. The effectiveness of any TTI hinges on a concept called Activation Energy **(**E_a) Matching. Every food spoilage reaction, including microbial growth, enzyme activity, and chemical breakdown, has a specific activation energy (E_a). This energy determines how much faster spoilage happens as the temperature increases. The chemical or biological reaction in the TTI that leads to the color change must have an E_a very similar to the E_a of the food spoilage. As a result, when a product experiences excessive heat, both food spoilage and the TTI color change speed up at the same rate. This ensures that the TTI's visual endpoint, such as turning black, precisely aligns with the moment the food is considered spoiled or unsafe, no matter how many times the temperature changes. These advanced TTIs, such as VITSAB or OnVu, work through an enzyme-substrate reaction. This reaction either causes a change in pH or releases a dye that can be detected. An enzyme, such as esterase, breaks down a substrate, like tripropionin, into an acid. This process leads to a drop in local pH. It causes a color change in a co-immobilized pH indicator dye.

The convergence of sensors and digital communication is defining the future of intelligent packaging (Bibi *et al*., 2017). Chemical and biosensors are micro- or nano-scale devices that detect specific chemical components, such as pH, VOCs, and metabolites, or biological agents like pathogens. They convert the detection into an electrical signal (Mahalik & Nambiar, 2010). Electrochemical Sensors are used to detect specific metabolites like Xanthine in fish degradation (Devi *et al*., 2013). The Radio Frequency Identification (RFID) Tags work with sensors to become smart sensor tags. They have memory, can be read without a direct line of sight, and can send data wirelessly to a remote reader. Further, the integration of temperature sensors into RFID tags allows for continuous data logging of the cold chain history. This data, combined with quality decay algorithms, provides a dynamic, predictive shelf-life assessment (IoT-Enabled Biosensors, 2025). RFID integration helps improve logistics by allowing systems to enforce a FEFO stock issuing policy based on real product quality instead of just the production date (Smits *et al*., 2012).

Fabrication, Nanotechnology, and Commercialization Challenges

The cost-effective and large-scale manufacturing of FIs needs improvements in printing and material science. The Inkjet printing is favored for applying chemical and natural dye formulations onto surfaces with high precision and minimal waste. It allows for quick and affordable production (Shao *et al*., 2021). Nanomaterials are used to improve FI performance with enhanced sensitivity and stability. Nanoparticles offer a large surface area compared to their volume. This greatly increases the sensor's interaction with target volatile molecules, which improves sensitivity. Nanocrystals from cellulose or chitin are used to encapsulate and protect unstable pigments such as anthocyanins. This improves their UV barrier properties and color stability (Liu *et al*., 2024).

The biggest challenge is making sure financial institutions are safe for food contact. This mainly involves concerns about chemical migration. The EU has set the global benchmark for Food Contact Material (FCM) safety. Regulation (EC) No 1935/2004 sets the general principle that FCMs must not endanger human health. Commission Regulation (EU) No 10/2011 is for plastic FCMs, limits are set via the Overall Migration Limit (OML) and Specific Migration Limits (SMLs) (EUR-Lex, 2011). The high regulatory burden on synthetic chemicals has strongly pushed development towards Natural Pigments (GRAS status) to mitigate migration concerns. The US Food and Drug Administration (FDA) requires that all substances in intelligent packaging must be shown to be safe for their intended use. This involves thorough testing to make sure migration levels are below safety limits.

Future Perspectives and Emerging Trends

The future growth of FIs focuses on addressing commercialization obstacles. It also aims to use digital technologies to build advanced, connected monitoring systems. The next generation of indicators will be multifunctional. They will track several physical and chemical changes at the same time for a complete quality assessment. Creating distinct reaction zones on a single label, with each zone responding to a different metabolite (e.g., one spot for TVB-N, another for CO_2) and a hybrid model by combining a TTI (cumulative history) with a chemical indicator (current spoilage status) on the same package. The most transformative trend is the integration of FIs with the IoT ecosystem. Sensors in packaging materials collect data on temperature, humidity, and gas levels. They send this information to cloud computing platforms. Machine Learning (ML) algorithms analyze real-time sensor data and compare it to quality decay models. This helps predict the remaining shelf life in real time. As a result, logistics managers can identify high-risk shipments and adjust pricing ahead of time (IoT-Enabled Biosensors, 2025). Consumers can use a smartphone to scan a QR code or an NFC/RFID tag. This shows the indicator's status, like "70% Fresh," and provides traceability information. It helps build greater trust (Shao *et al*., 2021). Future FIs must align with the circular economy. The biodegradable Packaging utilizes fully biodegradable substrates (e.g., starch, cellulose, chitosan) derived from biopolymers to host the indicator dyes (Persistence Market Research, 2031). The ultimate form of safe indicators containing natural pigments used in edible films, which can be consumed with the food product itself, eliminating migration and disposal problems.

Conclusion

Freshness Indicators are not just a fancy label. They are an important technological response to the global problems of food waste and safety. They mark the last stage of packaging evolution, changing the package from a passive container into an active, communicating sentinel. While simple visual indicators made from safe natural pigments like Anthocyanins are gaining popularity, the future is in advanced Data Carrier Systems. The smooth combination of Time-Temperature Indicators, electrochemical sensors, and the Internet of Things, driven by AI models that predict outcomes, is changing food logistics. This shift moves us from a fixed-date system to a flexible, data-driven supply chain. The main challenges that still exist, such as lowering the high production costs of advanced sensors and ensuring they meet regulations, are being tackled through improvements in printing technology, green chemistry, and nanotechnology. In the end, the broad use of integrated freshness indicators is not just a packaging innovation; it is a crucial part of creating a more efficient, safe, and sustainable global food supply chain.

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AGROWASTE UTILIZATION IN AQUACULTURE

Anusha Garg[1*], Shivendra Kumar[1], Sujit Kumar Nayak[1] and Patekar Prakash[1*]

[1]Dr Rajendra Prasad Central Agricultural University, Pusa
*Corresponding Email: 2402201005@rpcau.ac.in

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Introduction

The world's population has grown from 2.49 billion in 1950 to 8.19 billion in 2025. It is expected to reach about 9 billion by 2050 and around 11 billion by 2100 (Kaul B *et al.*, 2022). As the world's population keeps increasing, the demand of food is also rising, and to meet this growing need, aquaculture especially fish farming has expanded quickly. Fish is highly nutritious because it provides high amount protein, calcium, vitamin D, contain very low amount of cholesterol and also rich in unsaturated fatty acids, especially omega-3 essential fatty acids (Mohanty *et al.*, 2019). To maintain high nutritional value of fish, it is essential to ensure a consistent supply of nutritious and high-quality fish feed. Nowadays, although the cost of commercial fish feed continues to rise, global demand remains high due to its recognized nutritional benefits. Incorporating agri-food waste as a partial or complete component of fish diets represents a promising strategy to reduce production cost while promoting strategy to reduce production costs while promoting resource efficiency within a circular economy framework (Bertocci *et al.*,2022). India produces an estimated 500–550 million tonnes of crop residues each year (Abdullah *et al.*, 2021; Kataki *et al.*, 2023a). This represents a very large amount of agricultural waste. Agricultural wastes refer to the residues generated during the cultivation and processing of agricultural products and these materials are non-product outputs of agricultural production that may hold potential benefits for humans. However, their economic value is often lower than the costs associated with their collection, transportation, and processing. Still, using these agricultural wastes in aquaculture can turn low-value leftovers into useful resources, helping to reduce waste and support sustainable practices (Mamo *et al.*, 2022). Agro-waste includes around 89 million tonnes of wheat, 56 million tonnes of sugarcane, 47 million tonnes of cotton, 43 million tonnes of rice, and 23 million tonnes of fruits and vegetables (Athwal *et al.*, 2023) also include crop residues (straw, husks, stalks), animal waste, agro-industrial waste, and unutilized portions of plants (Hoang *et al.*, 2024a).As per estimates, India generates more than 500 million tons of agricultural waste each year, of which only about half is used successfully (Singh & Prabha, 2019).

Different types of agro-waste

Agro-wastes are generated by different types of agricultural processes and operations (Obi et al.,2016). Agro-waste can be broadly classified into three categories including natural crop residue, agro-industrial waste and livestock waste. Crop residues and agro-industrial wastes constitute the most abundant categories of agricultural by-products, generated in substantial quantities on a daily and sustainable basis (Rizal et al., 2021). These agro residues including molasses, husks, bagasse, seed, leaves, stems, pulp, peel etc. represent valuable biomass resources that can be utilized for fish feed formulation, soil enhancement, organic fertilizer production and several other applications. The proper management and reuse can conotvert agro-waste into valuable resources such as biofertilizers, bioenergy, or feed components, prhomoting environmental sustainability (Mathieu *et al.*, 1995).

Utilization of agro-waste in aquaculture

Agro waste-based feed supplements for fish growth-

Agro-industrial wastes, residues, and by-products are valuable resources that can be used as low-cost ingredients in fish feed and it contain useful molecules, bioactive compounds, and hormones that can promote fish growth and improve the quality of fish meat when included in their diet (Bertocci *et al*., 2022). Agro waste are rich in organic and inorganic compounds, sugars, and various phenolic compounds. These phenolic compounds have medicinal value because of their anti-inflammatory, antibacterial, immunomodulatory, and antifungal properties (Bala *et al*., 2023). Lignocellulosic agricultural by-products such as wheat straw, wheat and rice bran, spent coffee grounds, and sawdust are known to be rich sources of phenolic compounds. Because of their strong antioxidant and antimicrobial properties, these by-products have great potential for use in various industrial applications (Fermoso *et al*., 2018). Many researchers' reports have shown that the agro waste can enhance fish growth and improve the overall quality of the fish when included in their diet. According to Kaur and Saxena (2004), feeding *C. catla* and *L. rohita* a diet with 30% brewery waste led to better growth and higher weight gain compared to fish fed the normal control diet. Singh *et al*. (2015) reported that rohu juveniles can utilize ghee residue up to a 24% level in their diet. They also observed that adding ghee residue increases the PUFA content in fish, which is beneficial for human health (Das *et al*., 2009). According to Singh *et al*. (2016), jute leaf powder can be safely included in the diet of rohu fingerlings up to a 20% level.

Agro waste – derived biofertilizer-

Biofertilizer was prepared using the solid-state fermentation method and applied to a vegetable garden. Experimental results showed that plant samples treated with biofertilizers made from watermelon, papaya, and banana wastes exhibited improved physical properties. Among them, the biofertilizer made from banana waste had the highest potassium concentration (Lim *et al*., 2015).

Agro waste Conversion into Nanomaterials-

Agricultural wastes can be effectively converted into valuable nanomaterials, including nano capsules, which serve as carriers for bioactive compounds. Nanoencapsulation is an effective technique used to protect various food components from unfavorable physiological conditions or degradation. It also helps mask undesirable odors and flavors, thereby improving the overall quality and acceptability of food products (Bala *et al*., 2023).

Biochar production from Agro-waste

Biochar is a good utilization of agro waste in aquaculture. Biochar is a porous, carbon-rich material produced through the thermochemical decomposition of biomass under limited oxygen conditions, a process known as pyrolysis (Fabian *et al*., 1993). A variety of organic waste materials can be used as feedstocks for biochar production, including oak wood, sugarcane bagasse, sewage sludge, coffee husks, and other agricultural or industrial residues (Huyen *et al*., 2024). Many studies have shown that biochar can be used to make the soil more fertile and also stores carbon in the ground. It is also used in wastewater treatment to remove metals and other harmful substances, helping to clean the water. In addition, it can act as a natural catalyst and eco-friendly material to remove different types of pollutants and reduce greenhouse gas emissions (Yu *et al*.,2009; Cha *et al*.,2016; Inyang *et al*., 2016).

Conclusion

Agro-waste are seen as useless, but in aquaculture, they can be helpful. India, along with other developing countries, produces large amounts of crop residues and agro-industrial by-products every year, much of which remains underutilized. Effective management and reuse of agricultural wastes can transform them into valuable resources for aquaculture and other industries. In aquaculture, agro-wastes can serve as cost-effective non conventional feed ingredients in fish feed, sources of bioactive compounds. They can also be converted into useful products like biofertilizers, biochar, and nanomaterials, promoting circular and sustainable production systems. Using agricultural wastes in aquaculture not only reduces environmental pollution but also enhances resource efficiency, supports fish health and growth, and contributes to sustainable food production. Therefore, turning agricultural residues into valuable inputs represents a promising step toward a cleaner environment and a more sustainable aquaculture production.

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THE IMPORTANCE OF THE GUT MICROBIOME IN THE CHINESE FRUIT FLY (*Bactrocera minax*)

R. Yonzone[1] and M. Soniya Devi[2*]

[1]College of Agriculture (Extended Campus), UBKV, Majhian, Dakshin Dinajpur,WB
[2]College of Horticulture, Central Agricultural University (Imphal), Bermiok Sikkim,
*Corresponding Email: rakesh@ubkv.ac.in

Introduction

The Chinese fruit fly (*Bactrocera minax*) is one of the most damaging pests of citrus crops in Asia, particularly in regions that cultivate mandarin oranges. The severe economic impact of B. minax stems from its unique biology: it is univoltine, producing only one generation a year, yet its larvae cause extensive internal fruit damage and premature fruit drop. While traditional research on fruit flies has focused on their physiology, genetics, and chemical ecology, recent scientific attention has shifted toward a previously underappreciated but crucial aspect of their biology: the gut microbiome. The gut microbiome, a complex community of bacteria, fungi, and other microorganisms living in the digestive tract, plays essential roles in digestion, immunity, growth, reproduction, and behavior. In fruit fly species, including *B. minax*, gut microbes have emerged as key contributors to adaptability, survival, and pest status. Understanding these microbial communities offers opportunities not only for a deeper insight into fruit fly ecology but also for the development of innovative, environmentally friendly pest management strategies. This article explores the composition, functions, and ecological significance of the gut microbiome of *Bactrocera minax*, emphasizing how this microbial partnership shapes the biology of this pest and how it may be harnessed for sustainable control.

Composition of the Gut Microbiome in *Bactrocera minax*

Although research on *B. minax* is not as extensive as that on the Mediterranean fruit fly or the Oriental fruit fly, available studies reveal that the species harbors diverse microbial communities dominated by bacterial groups common in other Tephritid fruit flies.

Dominant Microbial Groups

The gut microbiome of *B. minax* typically includes:

- **Proteobacteria** (especially *Enterobacter*, *Klebsiella*, *Pseudomonas*)
- **Firmicutes** (e.g., *Lactobacillus*, *Bacillus*)
- **Actinobacteria**
- **Acetobacteraceae**, known to support sugar-rich diets

These bacteria vary in abundance depending on the fly’s developmental stage (egg, larva, pupa, and adult) and environmental factors, such as diet, host fruit chemistry, and orchard microbiota.

Stage-Specific Variation

- **Larvae** harbor microbes that specialize in breaking down fruit pulp, thereby enhancing nutrient extraction.
- **Pupae** experience reduced microbial diversity due to gut restructuring during metamorphosis.

- **Adults** acquire additional microbes from environmental sources, such as nectar, fruit surfaces, and soil.

These dynamic changes show that the microbiome is not static but rather adjusts according to the physiological needs of the insect.

Role of the Gut Microbiome in Nutrition
One of the most fundamental functions of the gut microbiome is to aid nutrition. *B. minax* larvae feed inside citrus fruit, where they are exposed to acidic conditions and secondary metabolites produced by the fruit. The microbiome helps overcome these challenges.

Digestive Support
Gut bacteria help:

- Break down complex sugars and plant polymers
- Convert nutrients into readily absorbable forms
- Detoxify compounds that would otherwise inhibit larval development

Several microbes produce enzymes, such as pectinases and cellulases, enabling larvae to digest fruit tissues more efficiently than they could with endogenous enzymes alone.

Nitrogen Fixation and Recycling
Fruit pulp is rich in carbohydrates but is often poor in nitrogen. Some gut bacteria can:

- Fix atmospheric nitrogen
- Recycle nitrogenous waste into amino acids

This allows larvae to grow rapidly despite nutritionally imbalanced diets.

Relationship Between the Gut Microbiome and Detoxification
Citrus fruits contain defensive compounds, such as essential oils, limonoids, and flavonoids, which can inhibit insect feeding. The B. minax microbiome helps detoxify these compounds.

Microbial Detoxification Mechanisms
Gut bacteria can:

- Degrade toxic plant secondary metabolites
- Modify chemicals to less harmful forms
- Enhance the fly's tolerance to natural fruit defense chemicals

These detoxification abilities are part of what enable *B. minax* larvae to survive inside highly defended citrus tissues, contributing to the species' pest status.

Impact on Development and Survival
Gut microbes influence multiple developmental processes, directly affecting the success of flies as pests.

Larval Development
Larvae deprived of their microbiome often show:

- Slower growth
- Reduced body mass
- Higher mortality rates

This highlights the contribution of the microbiome to digestion, immunity, and nutrient absorption.

Pupal Success and Adult Emergence
A healthy microbiome supports the following:
- Smooth transition through metamorphosis
- Higher pupal survival rates
- Stronger adult flies capable of efficient dispersal and reproduction

In summary, the microbiome affects survival across multiple life stages.

Influence on Reproduction
Gut microbes have been shown to influence the reproductive success of several fruit fly species, including *B. minax*.

Enhanced Mating Success
Some gut bacteria produce volatile or pheromone-like compounds that:
- Increase male attractiveness
- Influence mating success
- Improve courtship ability

This suggests a symbiotic link between microbial activity and reproductive behaviors.

Egg Viability
Females with richer gut microbiomes often experience:
- Produce healthier eggs
- Show higher fecundity
- Lay eggs more efficiently in host fruit

This makes the microbiome a critical factor in population growth and pest management.

Role in Immunity and Disease Resistance
The gut microbiome provides essential immune support to the host.

Microbial Protection
Beneficial microorganisms
- Compete with pathogens for space and nutrients
- Produce antimicrobial compounds
- Stimulate the fly's immune system

This defensive role reduces the likelihood of infections that could hinder development or reproduction in the host.

Environmental Stress Tolerance
A healthy microbiome also helps *B. minax* withstand environmental stresses, such as
- Temperature fluctuations
- Host fruit variability
- Exposure to natural enemies

Thus, the microbiome acts as an internal line of defense for flies.

Microbiome Transmission: How *B. minax* Maintains Its Microbial Partners
Gut microbes can be transmitted via:
- Vertically—from mother to offspring (e.g., through egg smearing)
- Horizontally—from the environment, host fruit, or other flies

This flexible microbial acquisition provides *B. minax* with ecological adaptability, particularly when it moves into new citrus-growing regions.

Implications for Pest Management

Understanding the gut microbiome of *B. minax* opens new possibilities for developing ecological and organic pest management strategies.

1. Paratransgenesis

This approach involves genetically altering symbiotic bacteria to produce substances that are harmful to the host insect.

- Genetically modified bacteria can disrupt development and reproduction.
- They can spread naturally among fly populations.

Although still experimental, this strategy has promising potential for clinical application.

2. Microbiome Disruption

Targeting the gut microbiome using

- Plant-based antimicrobial compounds
- Soil microbial competitors
- Bacterial inhibitors from natural sources

These methods may weaken flies by disrupting their digestion, immunity, or reproduction.

3. Enhanced Biological Control

Microbiome research can improve the effectiveness of biological agents.

- Entomopathogenic fungi
- Nematodes
- Parasitoids

Some microbes may increase susceptibility to these natural enemies of the host.

4. Improved Bait Formulations

Knowledge of microbial nutrient preferences enables the development of

- More attractive protein baits
- Better feeding stimulants

These methods can help suppress adult populations more effectively.

Overall, integrating microbiome-based strategies with traditional organic approaches could lead to more sustainable citrus-pest management.

Conclusion

The gut microbiome of the Chinese fruit fly (*Bactrocera minax*) is a vital component of insect biology, influencing digestion, detoxification, development, immunity, and reproduction. This internal community of microorganisms plays a major role in the fly’s ability to thrive in citrus environments and cause significant agricultural harm. As research continues to uncover the intricate interactions between *B. minax* and its microbial symbionts, new opportunities for environmentally friendly pest control strategies will emerge. Understanding and potentially manipulating the gut microbiome offers a promising approach to sustainable agriculture. By integrating microbiome-based tools with ecological and organic management practices, citrus growers can achieve more effective long-term suppression of *B. minax* populations, thereby reducing crop losses while supporting environmental health.

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Agrobacterium-MEDIATED GENE TRANSFER

M. Sowbaranigha[1] and S. Vignesh[2]

[1]Department of Plant Pathology, AC&RI, Coimbatore
[3]Department of Plant Biotechnology, AC&RI, Coimbatore
*Corresponding Email: sowbaranigham@gmail.com

Agrobacterium-mediated gene Transfer is one of the important methods for genetically modified or transgenic plants in the biotechnology aspect for improving crop yield, nutrient quality, disease resistance, abiotic and biotic stress tolerances. This soil bacterium has naturally transferred the DNA segment and integrated it into the plant genome. The researcher takes advantage of this natural mechanism by removing the T DNA (tumour-causing gene) from bacteria and inserting the desired gene, paving the way for a transgenic crop. It was discovered by Mary-Dell Chilton, Jeff Schell, and Marc Van Montagu in 1970s.

Agrobacterium tumefaciens is a Gram-negative bacterium, soil-borne, strictly aerobic, rod-shaped with six flagella. It is a phytopathogen, but the researcher considers a natural plant genetic engineer. The bacterium infects the damaged tissues of the plant and causes the crown gall disease. Which is the transfer of the Ti plasmid called T-DNA. Those that carry the code of protein help to biosynthesize the plant hormones such as auxin, cytokinin, and plant metabolites such as opines and agropines, which serve as the plant proliferation and source of energy and carbon, respectively. The Ti plasmid is a circular DNA segment, approximately 200kb, and T-DNA is 12 to 24 kb; these are based on their bacterial stain. The nopaline stain has two octopine, such as TL id 14 kb and TR is 7 kb. The T-DNA has three regions: the T-DNA region is a code for a protein and is flanked by left and right borders of the DNA sequences; The virulence region is responsible for the gene transfer of T-DNA into the host gene. And identify the nine operons such as (virA, virG, virB1, virC1, virD1, D2, D4, virE1, E2) and the opine catabolism region involves the uptake of protein and metabolism of opines and also helps to maintain the stability of the Ti plasmid.

T-DNA transfer and integration

The *Agrobacterium tumefaciens* infects the wounds and damages the tissues of the plant. These plants induced the phenolic compounds, sugar and amino acid. These molecules act as a signal that attracts the bacteria to the sites. *Agrobacterium tumefaciens* detects the molecules through the cell membranes. The gene is VirA/VirG; virA acts as the sensor and Vir G receives the phosphorylation through virA and activates the virulence genes (VirB, VirC, VirD, VirE, and VirF), which are needed for the T-DNA transfer. The T-DNA region from the Ti plasmid (tumour-inducing plasmid) makes a nick at the border sequences by VirD1/ VirD2. Following these, virD2 covalently attached to the 5′ end of the ssT-DNA and was coated with VirE protein along with the T-DNA, forming the nuclear protein complex called the T complex. To prevent degradation, the nucleases. The t-complex is exported from the plant cell through the Type IV Secretion System (T4SS), which acts as a molecular syringe to translocate DNA and protein effector across the bacterial and plant cell membranes. In the cytoplasm, the T complex enters to nucleus with the help of signals on virD2 and virE2. VirF, another effector protein, helps the uncoating of the T-DNA and integrates into the plant genome. These integrated T-DNA genes express the production of auxin and Cytokinins, which leads to cell proliferation and crown gall formation. Moreover, T-DNA directly synthesizes the opines and amino acids as the nutrient sources for *A. tumefaciens* and manipulates the plant metabolism for its benefits.

Table1: Role of Vir Gens

Gene	Function
Vir A	Sensor protein, it activates the phosphorylates vir gene
Vir B	Membrane protein, It forms a channel for transporting the T-DNA
Vir C	Involve in the unwinding of DNA
Vir D	Vir-D1 has topoisomerase activity, virD2 has endonuclease activity
Vir E	Prevent and guide the T-DNA
Vir F	Help the T-DNA for entry to plant nucleus
Vir G	Vir-D1 has topoisomerase activity, virD2 has endonuclease activity

Modified Ti plasmid

In modifying the Ti plasmid, it inactivates or removes the oncogenes which is responsible for the overproduction of plant hormones and opine synthesis, so that it no longer induces tumors. In their place, insert the desirable gene and the selectable marker gene within the T-DNA border.

For instance: SEV series, which includes the right border and phytohormone gene responsible for the production of plant hormones, is removed and inserted into the bacterial kanamycin resistance gene, while in the left border and small portion of left segment called left inside Homology (LIH). Similarly, *Agrobacterium* strains carry intrinsic antibiotic resistances, so don't use a vector that has the same antibiotic marker as the strain's resistance selection will fail. EHA101 is resistant to kanamycin, while the commonly used vector pBIN19 uses kanamycin for selection. That overlap makes it difficult to distinguish cells that actually received the vector. Instead, use a strain whose resistance marker is different from the vector's antibiotic. For instance, choose EHA105 (rifampicin-resistant) together with a kanamycin-marked vector; select transformants on plates containing rifampicin + kanamycin so you select for both the Agrobacterium strain and the vector.

In the pGV series, the phytohormone genes are excised and replaced with a fragment of the pBR322 vector, keeping the left and right border sequences and the nopaline synthase gene intact. To overcome the problem of the large Ti plasmid size and lack of suitable restriction sites, intermediate vectors (small pBR322-based plasmids containing T-DNA) are used. These plasmids can replicate in E. coli but not in A. tumefaciens, and when transferred to the latter via conjugation, homologous recombination occurs between the intermediate vector and the disarmed Ti plasmid, producing a co-integrated T-DNA structure ready for plant transformation.

Table 2: *Agrobacterium* resistance stain

Stain	Chromosome	Ti plasmid	Antibiotic resistances	Plants
AGL-1	C68	PTiBO542	Rifampicin	Maize and monocot
Gv3101	C58	pMP90	Rifampicin, Gentamicin	Potato. soyabean
LBA4404	Ach 5	Pal4404	Rifampicin	Tomato, Tobacco

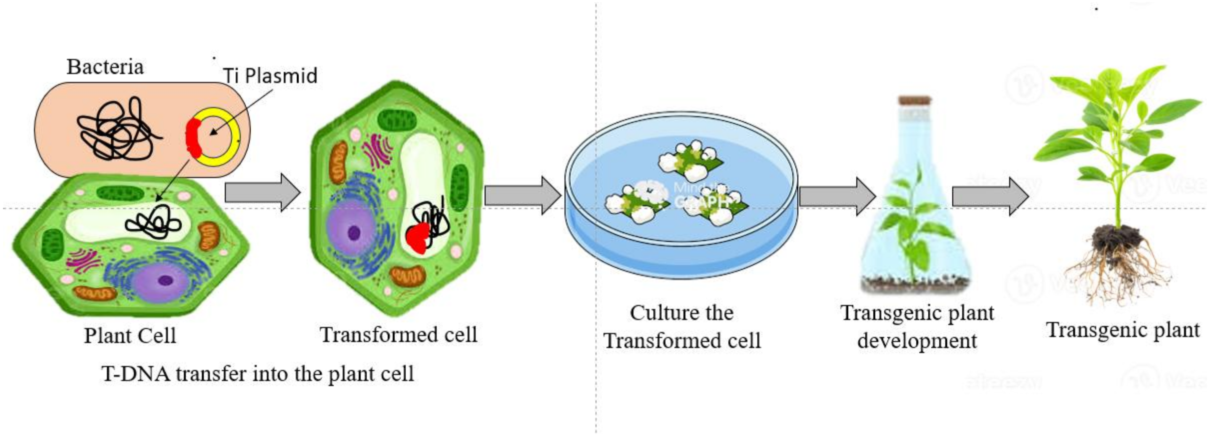

Fig: *Agrobacterium*-Mediated Gene Transfer

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AI AND AUTOMATION IN POSTHARVEST MANAGEMENT

Nalanda Acharya

Research Scholar, Department of Pomology and Postharvest Technology,
Uttar Banga Krishi Viswavidyalaya, Pundibari, West Bengal-736165.
*Corresponding Email: nalandaacharya2018@gmail.com

Introduction

Rapid developments in automation and artificial intelligence (AI) are revolutionizing post-harvest technology and providing creative ways to raise food safety, quality, and supply chain effectiveness. By streamlining procedures like sorting, grading, packaging, and microbial detection, artificial intelligence (AI) technologies like machine learning, computer vision, and IoT integration are decreasing food waste and increasing shelf life. Additionally, transportation and inventory management are becoming more efficient thanks to AI-powered robotics and smart warehouses. Rapid advancements in artificial intelligence (AI) and automation are transforming post-harvest technology and offering innovative approaches to improve food safety, quality, and supply chain efficiency. Artificial intelligence (AI) technologies like machine learning, computer vision, and IoT integration are reducing food waste and extending shelf life by optimizing processes like sorting, grading, packaging, and germ detection. Additionally, AI-powered robotics and smart warehouses are improving the efficiency of inventory management and transportation.

Role of Automation and AI in Post-Harvest

Automation and Artificial Intelligence have significantly transformed post-harvest operations by improving efficiency, consistency, and quality in food processing, storage, transportation, and distribution (Pathmanaban *et al.*, 2023) Key roles of automation and AI include robotics for handling, real-time monitoring and quality control, automated sorting and grading, and predictive analytics for shelf-life and storage optimization and packaging, supply chain and logistics optimization, inventory management and demand forecasting, blockchain and artificial intelligence integration, energy sustainability and efficiency, and sustainable packaging options. Compared to human inspectors, AI-driven visual inspection systems examine food goods for flaws and quality issues more quickly and precisely (Dhal & Kar, 2023) Furthermore, recent advancements in smart systems for farm machinery have demonstrated significant potential in improving soil fertility and crop productivity (Laskar *et al.*, 2024) Integrating AI-driven technologies into farm machinery enables precise soil monitoring, nutrient management, and tailored crop care. These developments support overall agricultural efficiency, aligning with ongoing innovations in automation and predictive analytics. AI-driven route planning and transportation optimize transportation routes for delivering food products from farms to distribution centers and retailers. AI-driven predictive analytics models forecast consumer demand for various food products, optimizing inventory levels and reducing waste. Blockchain and AI integration enhance food traceability and transparency, allowing consumers and producers to track the entire journey of food products from farm to table (Padhiary and Roy, 2024) This fosters trust and transparency in the food supply chain, increasing consumer confidence, reduced food fraud, and enhanced food safety.

Emerging Trends in Automation and AI Integration

The integration of automation and AI in post-harvest technologies is rapidly evolving, driven by advancements in machine learning, robotics, and sensor technology. Key trends include AI-enhanced predictive analytics for crop harvesting and demand forecasting, robotic automation in sorting, grading, and packaging, smart packaging with AI integration, Blockchain and AI for traceability and transparency (Rashid and Kausik, 2024) advanced AI for real-time microbial detection and safety monitoring, autonomous vehicles and drones for logistics and supply chain efficiency, AI in precision agriculture for post-harvest optimization (Debnath *et al.*, 2024) AI-powered environmental control systems in cold storage, AI for customizing post-harvest treatments (e.g., Ripening, Shelf-life Extension), sustainability and circular economy initiatives through AI, and AI for customizing post-harvest treatments. The integration of AI and IoT in farm machinery is driving advancements in precision agriculture, enabling real-time data collection and analysis for optimizing soil management, crop productivity, and sustainability (Hoque and Padhiary, 2024).

Post-harvest challenges

Challenges are crucial considerations in maintaining food quality, safety, and minimizing waste after harvest. One of the primary challenges is quality preservation, which includes ensuring proper temperature control and humidity regulation during storage, as these factors significantly impact the food's shelf life and nutritional value (Amit *et al.*, 2017) Improper handling, storage, and transportation often lead to quality deterioration, such as bruising, spoilage, or loss of nutrients. Another major issue is food losses, which occur due to spoilage, microbial contamination, or physical damage during handling and transit. These losses not only have a negative economic impact, but they also contribute to environmental concerns as large amounts of food are wasted. Furthermore, supply chain complexity presents additional challenges, with food passing through multiple steps from farm to table. Each step requires careful coordination and efficient logistics to prevent delays, reduce costs, and ensure timely delivery (Moons *et al.*, 2019) These challenges highlight the need for advanced technologies and automation to optimize post-harvest operations, improve food od preservation, and reduce waste. Table 1 outlines post-harvest challenges in food processing and supply chains, including microbial contamination, spoilage, and logistical inefficiencies. It presents AI-driven solutions like predictive models, real-time monitoring, and optimization systems to improve food quality, reduce waste, and optimize supply chain operations. The table also highlights the paper's sections discussing these challenges and AI solutions.

Challenge	Description	AI Solution	References
Quality preservation	Maintaining food quality during postharvest handling and storage	AI models for real-time monitoring	(Lalpekhlua *et al.*, 2024)
Temperature control	Difficulty in maintaining ideal temperature during storage	AI-driven temperature optimization systems	(Dhal and Kar, 2024)
Microbial contamination	Spoilage and pathogens affecting food quality	AI for microbial detection using sensors	(Taiwo *et al.*, 2024)
Food waste	Losses due to spoilage or suboptimal conditions	Predictive analytics for shelf-life extension	(Karanth *et al.*, 2023)

Challenge	Description	AI Solution	References
Supply chain complexity	Difficulty in managing multiple stages of post-harvest processes	AI-based supply chain optimization	(Fadiji *et al.*, 2023)
Logistics inefficiency	Suboptimal transportation routes and scheduling	AI-powered route optimization and fleet management	(Dikshit *et al.*, 2023)
Storage management	Inefficient use of space and resources in storage facilities	AI for smart inventory management	(Ruiz *et al.*, 2024)
Environmental impact	Excessive energy consumption in food handling	AI for energy-efficient postharvest systems	(Kollia *et al.*, 2021)
Data scarcity	Lack of quality data for AI models and predictions	IoT and AI integration for data collection	(Bhat and Huang, 2021)
Regulatory compliance	Adhering to food safety standards	AI for monitoring compliance in real-time	(Vegesna *et al.*, 2024)

Conclusion

The way food is handled, stored, and transported is fast changing as a result of the integration of automation and artificial intelligence in post-harvest management. AI-driven technologies have shown great promise in improving sorting, grading, packaging, storage, and transportation, which will ultimately reduce food waste and increase shelf life. These technologies include machine learning, computer vision, the Internet of Things, and robotics. These developments improve sustainability, food safety, and supply chain transparency in addition to operating efficiency. AI-based solutions offer strong capabilities for predictive analytics, real-time monitoring, and astute decision-making, even in the face of obstacles like data shortages, regulatory compliance, and logistical inefficiencies. In order to increase food security, lessen environmental effect, and promote innovation in contemporary agriculture, it will be essential to continue using and developing AI and automation in post-harvest activities.

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STORED GRAIN PESTS AND THEIR MANAGEMENT

Aman Kumar[1*] and Radheshyam Ramkrishna Dhole[2]

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Sasaram, Rohtas – 821305
[2]Assistant Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Sasaram, Rohtas – 821305
*****Corresponding Email: akamankumar957040@gmail.com

Abstract

Stored grain pests pose a major challenge to food security and post-harvest systems around the world. Significant losses in both quantity and quality of grains occur during storage due to insect infestation, causing economic damage to farmers, traders and the grain industry. With rising global demand for food and increasing storage durations, the importance of robust grain protection practices has intensified. This article provides a comprehensive overview of stored grain pests and their management. It discusses the background of storage pest problems, key characteristics of major pests, methods of detection and control, and practical applications of integrated pest management (IPM) strategies. It highlights the need for eco-friendly, sustainable and advanced technologies to minimize losses. The paper concludes with future strategies focusing on digital surveillance, biological control and safe fumigants for long-term grain protection.

Background

Post-harvest losses owing to storage pests are a critical barrier to food security, particularly in developing countries. In India alone, losses due to storage pests have been estimated at 10–15% of total stored grains every year. Grains stored for consumption, trade or seed purposes are vulnerable to infestation by insects, mites and rodents. Climatic factors such as higher temperature and humidity play a central role in pest multiplication. Poor infrastructure, improper storage containers, lack of hygiene and limited awareness aggravate the problem.

Stored grain pests cause two types of damage. Primary damage occurs when insects directly feed on whole grains, creating holes and loss of weight. Secondary damage occurs due to feeding on broken grains, contamination by excreta, webbing and warmth generated by pest activity, which promotes molds. Infestation reduces nutritional quality, viability of seeds and marketability, threatening the livelihoods of farmers and grain traders. Hence, effective stored grain pest management is essential.

Key Features of Major Stored Grain Pests : Stored grain pests are classified as primary and secondary pests depending on their feeding habits.

1. Primary Pests : These pests attack whole grains even without prior damage.

- Rice weevil (*Sitophilus oryzae*): Small reddish-brown beetle that lays eggs inside kernels, causing internal damage.
- Lesser grain borer (*Rhyzopertha dominica*): Highly destructive; larvae and adults bore into grains leaving flour-like dust.

- Angoumois grain moth (*Sitotroga cerealella*): Larvae develop inside grains and feed on endosperm.
- Maize weevil (*Sitophilus zeamais*): Major pest of maize but also attacks rice and wheat.

2. Secondary Pests : These pests feed on broken grains, grain dust or grains already damaged by primary pests.

- Red flour beetle (*Tribolium castaneum*): Causes heating and mold formation; commonly infests flour and broken grains.
- Saw-toothed grain beetle (*Oryzaephilus surinamensis*): Fast breeder that contaminates grain heavily.
- Indian meal moth (*Plodia interpunctella*): Larvae create webbing, reducing quality of food commodities.
- Characteristics common to storage pests include high reproduction rate, short life cycle, and capacity to survive in unfavorable conditions, making control difficult.

Methods and Applications in Stored Grain Pest Management

A successful storage protection plan includes prevention, early detection and corrective action. Modern approaches emphasize an Integrated Pest Management (IPM) model combining multiple eco-friendly strategies.

1. Preventive Management

- Pre-storage sanitation: Cleaning storage structures, machinery and surroundings to eliminate hidden infestations.
- Sun-drying of grains: Reduces moisture to 10–12%, minimizing pest multiplication.
- Grading and screening: Removal of cracked kernels and foreign matter that attract pests.
- Use of airtight packaging: Hermetic bags, metal bins and silos restrict oxygen required for pest survival.
- Temperature control: Low temperature storage retards insect growth.

2. Monitoring and Detection

- Visual inspection: Identification of infested grains, frass and webbing.
- Probe traps and pitfall traps: Detect presence and density of insects.
- Acoustic sensors and CO_2 detection: Advanced systems identify early infestation without opening sacks.
- Early detection enables timely intervention and reduces treatment costs.

3. Physical Methods

- Heat treatment: Exposing grains to temperatures above 55°C kills insects in all life stages.
- Cold treatment: Suitable for small-scale storage in low-temperature chambers.
- Modified atmosphere storage: Use of CO_2 or nitrogen to displace oxygen and suffocate insects.
- Solarization: Grain bags are covered with polythene sheets to elevate temperature under sunlight.

4. Chemical Control : Chemical control is effective when used judiciously and safely.

- Insecticides for surface treatment: Malathion, cyfluthrin and chlorpyrifos protect storage structures.

- Grain protectants: Application of inert dusts, plant-based powders and approved formulations ensures long-term safety.
- Fumigation: Aluminium phosphide and phosphine gas are widely used for controlling high infestations. Strict safety measures are necessary to avoid residues.

5. Biological and Botanical Approaches : Environment-friendly approaches are gaining popularity.

- Botanical pesticides: Neem oil, eucalyptus oil, turmeric powder and pongamia extracts disrupt breeding and feeding.
- Predators and parasitoids: Species such as *Habrobracon hebetor* parasitize moth larvae.
- Entomopathogenic fungi: *Beauveria bassiana* and *Metarhizium anisopliae* infect pests without affecting grain quality.

6. Hermetic and ICT-enabled Storage Technologies

- Hermetic silos and Purdue Improved Crop Storage (PICS) bags provide airtight protection.
- Digital temperature and humidity sensors help monitor pest-favorable conditions.
- Mobile apps and AI-based advisory systems assist farmers in decision support.

Conclusion

Stored grain pest management is a critical component of post-harvest agriculture. Losses caused by pests not only reduce food quantity but also diminish nutritional value, seed viability and market price. An effective control strategy requires a holistic approach integrating preventive methods, regular monitoring, physical and biological treatments, and safe chemical interventions. The success of pest management not only improves food security but also enhances income for farmers and grain handlers. Awareness, training and adoption of improved storage structures play a key role in reducing post-harvest losses.

Future Strategy : To ensure long-term, sustainable grain storage security, future strategies must emphasize:

- Wider adoption of IPM-based storage management to minimize chemical dependence.
- Development of safer fumigants as alternatives to phosphine to address resistance issues.
- Expansion of hermetic storage solutions for farm-level and commercial storage.
- Bio-pesticide innovation involving microbial agents and botanical extracts.
- Digital surveillance systems using IoT sensors, robotics and machine learning for real-time monitoring.
- Capacity building programs to educate farmers, warehouse operators and traders on scientific storage practices.
- Implementing these strategies will support safe, sustainable and efficient grain preservation, contributing to global food security.

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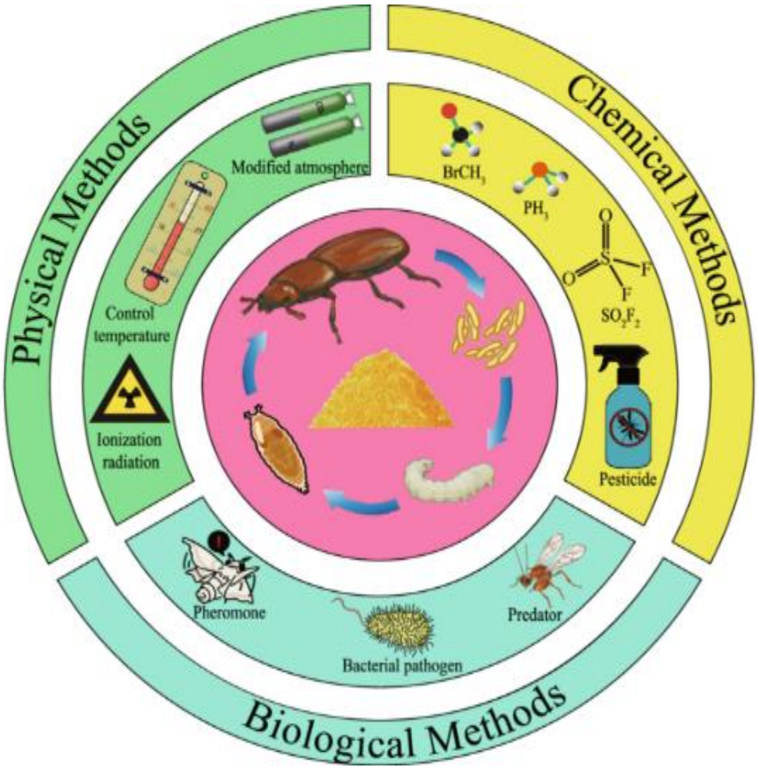

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FROM HARVEST TO MARKET: IMPROVING POSTHARVEST HANDLING AND VALUE-ADDED PRODUCTS OF SESAME

Adamu D. A* and Orimafo P. K.

Research Outreach Department,
Nigerian Stored Products Research Institute Ilorin, Nigeria
*Corresponding Email: adamu.davida@gmail.com

Abstract

Sesame (Sesamum indicum L.) is one of the world's oldest oilseed crops, valued for its high oil content, nutritional profile, and industrial applications. Despite its economic and nutritional importance, sesame production in many developing countries is constrained by poor postharvest handling practices, high losses, and limited value addition. In Nigeria, where sesame is a key non-oil export commodity, challenges such as poor storage, inadequate processing technologies, and lack of product diversification hinder its full economic potential. This paper reviews the postharvest handling of sesame and explores opportunities for developing value-added products, highlighting their importance, market prospects, and role in improving livelihoods and contributing to agricultural diversification.

Introduction

Sesame is an important oilseed crop cultivated in Asia, Africa, and Latin America, with Nigeria ranking among the top producers globally (FAO, 2021). It is valued for its high-quality edible oil, protein-rich cake, and diverse industrial applications in pharmaceuticals, cosmetics, and food industries (Bedigian, 2015). Globally, sesame production has been increasing due to rising demand for healthy oils, plant-based proteins, and functional foods (Mondal & Badigannavar, 2019).

Despite its potential, sesame faces significant challenges in the postharvest stage, where poor handling, inadequate drying, contamination, and pest infestation lead to substantial losses and reduced product quality. Moreover, limited development of value-added products restricts the contribution of sesame to household income, food security, and foreign exchange earnings in producing countries such as Nigeria.

This review examines sesame postharvest handling practices, explores existing and potential value-added products, and discusses their importance and market prospects in Nigeria and beyond.

Background to the Study

Sesame is a crop of antiquity, cultivated for over 3,000 years, often referred to as the "queen of oilseeds" due to its high oil content (45–60%) and stability (Pathak et al., 2014). It thrives in semi-arid tropical regions and is a major cash crop for smallholder farmers in northern Nigeria (Kano, Jigawa, Benue, and Nasarawa states).

The crop is gaining prominence as a non-oil export commodity, contributing significantly to Nigeria's agricultural export basket (CBN, 2020). However, inefficiencies in postharvest handling and limited processing capacity reduce competitiveness in the global sesame value chain.

In Nigeria and other sesame-producing countries, postharvest losses range between 20–30% due to poor harvesting, threshing, drying, and storage practices (Adekunle et al., 2018). Contamination from aflatoxins, dirt, and microbial load reduces quality, making exports susceptible to rejection in international markets. Additionally, the limited development of value-added products such as sesame oil, snacks, and cosmetics restricts economic returns to farmers. Without improved handling and processing, the full potential of sesame as a foreign exchange earner and food security crop cannot be realized. This article examines postharvest handling practices of sesame, identify and highlight value-added products derived from sesame, assess the importance and market potential of sesame value chains and recommend strategies for reducing losses and promoting product diversification.

Justification

Sesame is a high-value export crop with immense potential to boost rural livelihoods, reduce poverty, and contribute to Nigeria's non-oil economy. Strengthening its postharvest management and promoting value addition is justified by the need to reduce losses, increase farmer income, and position Nigeria competitively in the global sesame market.

Value-Added Products of Sesame

Value addition transforms raw sesame into diverse products with higher economic returns. Examples include:

i. Sesame oil: Used for cooking, pharmaceuticals, and cosmetics.
ii. Sesame cake/meal: A by-product rich in protein, suitable for livestock feed.
iii. Sesame flour: Used in bakery and confectionery.
iv. Snacks and condiments: Tahini, sesame bars, pastes, and roasted sesame.
v. Cosmetic products: Skin care oils, soaps, and hair care formulations.

Developing small-scale processing enterprises can enhance income opportunities for local farmers and entrepreneurs (Obiajunwa et al., 2020).

Importance of Sesame

i. Nutritional value: Rich in protein, oil, calcium, and antioxidants such as sesamol and sesamin.
ii. Economic significance: Provides cash income and foreign exchange earnings.
iii. Industrial uses: Ingredient in pharmaceuticals, cosmetics, and health foods.
iv. Livelihoods: Engages thousands of smallholder farmers in rural areas.

Market Prospects

Global demand for sesame is expanding, particularly in Asia (China, Japan, India) and the Middle East. Nigeria exports over 300,000 metric tons annually, making it one of Africa's leading exporters (FAO, 2021). However, to sustain and expand this market, Nigerian sesame must meet international quality standards, while diversification into oil, snacks, and cosmetics will expand domestic and regional markets.

Conclusion

Sesame holds immense potential as a multipurpose crop with nutritional, economic, and industrial benefits. However, challenges in postharvest handling and inadequate value addition limit its full potential in Nigeria. Improved handling practices, product diversification, and quality control are critical to enhancing its competitiveness in global and domestic markets.

Recommendations : The study therefore recommended that;

1. Government and donor agencies should train farmers and processors on improved harvesting, drying, and storage practices.
2. Promote investment in small- and medium-scale sesame processing enterprises.

3. Strengthen quality control and regulatory frameworks to meet export standards.
4. Support research into new sesame-based value-added products.
5. Develop market linkages and infrastructure to connect farmers with domestic and international buyers.

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MAJOR INSECT PESTS OF COLE CROPS AND THEIR CONTROL

Roushani Singh[1] and Radheshyam Dhole[2]

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Rohtas, Bihar- 821305
[2]Assistant Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Rohtas, Bihar- 821305
*Corresponding Email: roushanisingh147@gmail.com

Abstract

Cole crops—such as cabbage, cauliflower, broccoli, kale, and Brussels sprouts—are widely cultivated vegetables belonging to the family Brassicaceae. They play a significant role in nutritional security and agricultural economies worldwide. However, their cultivation is severely affected by various insect pests that attack from the nursery stage through harvesting. Major pests include the diamondback moth (*Plutella xylostella*), cabbage butterfly (*Pieris brassicae*), cabbage aphid (*Brevicoryne brassicae*), cabbage borer (*Hellula undalis*), cutworms (*Agrotis spp*.), leaf webber (*Crocidolomia pavonana*), and flea beetles (*Phyllotreta spp*.). These pests cause extensive damage by feeding on leaves, boring into stems and heads, and transmitting diseases, resulting in yield losses ranging from 20–80% if not properly managed. Effective management requires early detection, proper monitoring, and adoption of integrated pest management (IPM) techniques. Control methods such as cultural practices, biological control agents, botanicals, mechanical measures, and safe chemical alternatives can significantly reduce pest populations. This article provides a comprehensive overview of major cole crop pests, symptoms of infestation, and eco-friendly control strategies. Future prospects include the development of pest-resistant varieties, advanced biopesticides, and precision agriculture technologies for sustainable pest management. This review aims to assist farmers, researchers, and extension workers in implementing effective and environmentally safe pest control practices.

Key words: Cole crops, Insects, Control, Biological and Yield loss

Introduction

Cole crops are among the most important vegetables grown globally for their high nutritive value, adaptability, and economic importance. Cabbage, cauliflower, broccoli, turnip, and kale are rich sources of vitamins A, C, and K, minerals, fiber, and antioxidants. These crops are grown predominantly during the cool season and provide livelihoods to millions of small and marginal farmers.

However, cole crops are highly vulnerable to insect pests due to their soft foliage, succulent tissues, and glucosinolate compounds that attract herbivorous insects. Pest infestation can occur at all crop stages—from nursery to field establishment, head formation, and harvesting. Damage not only reduces yield but also affects market quality, making integrated pest control crucial. Historically, synthetic pesticides were heavily used to manage the pests, but their disadvantages—including residue accumulation, environmental degradation, pest resurgence, and development of resistance—have necessitated a shift towards eco-friendly pest management.

This article discusses the major insect pests affecting cole crops, their identification, biology, types of damage, detection methods, and effective control strategies, with emphasis on integrated and sustainable approaches.

Major Insect Pests of Cole Crops

1. Diamondback Moth (*Plutella xylostella*)

Description: Small grayish moth; larvae are green and active.

Damage: Creates window-like holes in leaves; severe defoliation; larvae also damage curds and heads.

Significance: Most destructive pest of cole crops worldwide.

2. Cabbage Butterfly (*Pieris brassicae*)

Description: Large white butterfly; velvety green larvae.

Damage: Larvae feed gregariously, causing serious leaf damage in early stages.

3. Cabbage Aphid (*Brevicoryne brassicae*)

Description: Soft-bodied, grayish aphids feeding in clusters.

Damage: Suck sap; produce honeydew; cause stunted growth, curling leaves, and disease transmission.

4. Cabbage Borer (*Hellula undalis*)

Description: Caterpillars bore into leaf stalks and heads.

Damage: Drooping of central leaves; holes and tunnels in heads; quality deterioration.

5. Leaf Webber (*Crocidolomia pavonana*)

Description: Larvae web leaves together and feed inside.

Damage: Skeletonization of leaves; major nursery pest.

6. Cutworms (*Agrotis spp*.)

Description: Nocturnal larvae that remain in soil during daytime.

Damage: Cut seedlings at ground level; major threat during early growth.

7. Flea Beetles (*Phyllotreta spp*.)

Description: Small, shiny beetles that jump when disturbed.

Damage: Shot-hole feeding on leaves; affects seedlings severely.

Methods of Detection

1. Regular Field Scouting

- Monitoring is essential twice a week during early crop stages.
- Inspect underside of leaves for diamondback moth larvae.
- Look for webbing to detect leaf webber.
- Examine growing points for cabbage borer entry holes.
- Check for cut or wilted seedlings indicating cutworm presence.

2. Economic Threshold Levels (ETLs)

- **Diamondback moth:** 1 larva/plant or 5 larvae/10 plants.
- **Cabbage aphid:** 20% plants infested.
- **Cabbage butterfly:** 2–3 larvae/plant.
- **Cutworm:** 5% plants damaged.

3. Light, Yellow Sticky, and Pheromone Traps

- Pheromone traps (*Plutella lure)* detect diamondback moth early.
- Yellow sticky traps monitor aphids.
- Light traps attract cutworm moths and leaf webber adults.

4. Nursery Monitoring

- Nursery beds are highly susceptible to leaf webber, flea beetles, and aphids.
- Regular inspection ensures early control.

5. Damage Symptom Identification

- Window panes on leaves → DBM
- Leaf webbing → Leaf webber
- Curled gray leaves with honeydew → Aphids
- Holes in heads → Cabbage borer
- Cut seedlings → Cutworm

Control Measures

A. Cultural and Preventive Control

1. Crop Rotation : Rotate cole crops with cereals or legumes to reduce pest carry-over.
2. Clean Cultivation : Remove plant residues that harbor pupae or eggs of DBM, leaf webber, and cutworms.
3. Healthy Nursery Management : Use raised beds, proper spacing, and net covers to prevent flea beetle and butterfly attack
4. Timely Sowing : Avoid late sowing to escape high pest pressure, especially cabbage butterfly and aphids.
5. Trap Crops : Use mustard as a trap crop to attract DBM and aphids; destroy infested plants regularly.

B. Mechanical and Physical Control

1. Hand Picking : Larvae of DBM, cabbage butterfly, and leaf webber can be manually removed in small fields.
2. Light Traps : Help reduce cutworm and leaf webber adult populations.
3. Net Covers : Protect nursery plants from butterflies and flea beetles.

C. Biological Control Measures

1. Parasitoids and Predators

a. Parasitoids

Cotesia plutellae: Effective larval parasitoid of diamondback moth.

Trichogramma brassicae: Egg parasitoid for DBM and cabbage butterfly.

Diadegma semiclausum: Excellent biocontrol agent in temperate regions.

b. Predators

- Ladybird beetles (Coccinellids) → Aphids
- Chrysoperla spp. (Green lacewings) → DBM larvae
- Spiders → Caterpillars and flea beetles

2. Entomopathogens

a. Bacillus thuringiensis (Bt)

- Highly effective against DBM, cabbage borer, and cabbage butterfly.
- Apply during evening for best results.

b. Beauveria bassiana & Metarhizium anisopliae

- Control larvae of DBM, cutworms, and flea beetles.

c. Nuclear Polyhedrosis Virus (NPV)

- Effective against leaf webber in some regions.

D. Botanical Pesticides

1. Neem-Based Extracts

- Neem seed kernel extract (NSKE 5%)
- Neem oil (2–3 ml/L)
- Effective against aphids, DBM, and leaf webber.

2. Garlic-Chilli Extract

- Repels caterpillars and flea beetles.

3. Custard Apple Leaf Extract

- Acts as an antifeedant for DBM.

E. Chemical Control (Safe & Selective Use)

Chemicals should be used only when pest levels exceed ETLs and after biological/botanical methods fail.

Recommended Options

- For DBM: Emamectin benzoate, spinosad (safer options).
- For aphids: Imidacloprid (soil drench) or flonicamid.
- For cutworm: Chlorantraniliprole.
- Rotate pesticides to prevent resistance.

Integrated Pest Management (IPM) for Cole Crops

A successful IPM strategy for cole crops includes:

- Use of pest-resistant varieties.
- Installation of pheromone traps (5–6/acre).
- Release of Trichogramma cards every 10 days.
- Weekly sprays of neem extract.
- Bt applications during high caterpillar activity.
- Regular field monitoring and ETL-based chemical use.
- IPM reduces chemical pesticide usage by 50–70% while providing sustainable pest suppression.

Conclusion

Cole crops are highly susceptible to a wide range of insect pests that cause significant economic losses. Early detection and timely intervention are crucial for minimizing damage. Among all pests, the diamondback moth remains the most destructive due to its rapid reproduction and resistance development. Other pests—such as cabbage butterfly, aphids, leaf webber, cabbage borer, and cutworms—also require integrated management strategies. A combination of cultural practices, biological control agents, botanicals, mechanical removal, and judicious pesticide use forms the foundation of sustainable pest management. Strengthening IPM adoption ensures healthier crops, safer food, and reduced environmental contamination. Farmers should be encouraged to rely more on eco-friendly approaches and less on chemical pesticides.

Future Prospects

The future of cole crop pest management lies in adopting innovative and sustainable technologies. Potential advancements include:

- Development of pest-resistant and biotech-enhanced varieties.
- Advanced biopesticides such as RNAi-based insect control, microbial consortia, and nano-biopesticides.
- Climate-smart forecasting tools to predict pest outbreaks based on temperature and humidity patterns.
- AI-based pest monitoring systems, drones, and smartphone apps for real-time field surveillance.
- Augmentation of natural enemies, including mass production of parasitoids like Cotesia plutellae.
- Improved pheromone-based mating disruption techniques for DBM.
- With increasing demand for safe vegetables and rising awareness about environmental protection, sustainable pest management will play a pivotal role in the future of cole crop production.

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TRADITION MEETS TECHNOLOGY: EMPOWERING INDIA'S ARTISANS IN THE DIGITAL AGE

Divya*, Nisha Arya, Somlata, Minakshi Sharma and Annu

Deptt. of Apparel and Textile Science, I.C. College of Community Science,
CCS HAU, Hisar, Haryana
*Corresponding author: divyadogra1997@gmail.com

Abstract

Modern technology is revitalizing India's ancient crafts by merging tradition with innovation. E-commerce platforms open global markets for remote artisans, granting direct access to consumers and preserving authentic techniques. Social media enables artisans to share behind-the-scenes narratives and form collaborative communities. Meanwhile, virtual reality archives meticulously document craft processes such as hand movements and loom techniques, ensuring knowledge transfer to future generations. Finally, block chain certification secures provenance and ensures fair compensation through transparent transactions, combating counterfeits. Together, these technologies empower artisans to thrive culturally and economically in a digital age.

Keywords: Global markets, craft archives, digital empowerment, heritage preservation and E-commerce.

Introduction

India's ancient craft hubs, places like Kutch, Varanasi, Moradabad and Bhuj, are alive once again with the rhythmic song of handlooms weaving through narrow alleys and the careful hands of artisans shaping colourful fabrics, intricate jewellery and exquisite pottery. These craftsmen, whose skills have been lovingly passed down through generations, once faced limited market access, shrinking demand and the fear that their traditions might vanish in an increasingly industrial world. Yet today, technology, often label as a tool for mass production and automation, is proving to be a powerful ally in preserving and elevating India's handmade heritage. Across the country, a vibrant synergy is unfolding where centuries-old techniques harmonize with modern innovations: E-commerce platforms now act as digital bridges, connecting artisans directly to global buyers who value authentic, handcrafted goods. Social media gives voice to their stories, weaving in the rich cultural narratives behind each creation and bringing their work to life for new audiences. Blockchain technology offers transparent certification, ensuring each piece's authenticity and provenance are securely documented, protecting both the craft and the crafts people. This fusion of tradition and innovation is more than preservation; it's a renaissance. It's reinvigorating entire communities, breathing new life into the artisanal economy and empowering craftsmen and women to carry on their legacy with dignity and pride while sharing India's vibrant cultural tapestry with the world.

The E-Commerce Revolution: Crafting Global Marketplaces

One of the most transformative effects of the digital era on traditional crafts has been the democratization of market access. In the past, artisans relied heavily on local middlemen and limited physical marketplaces, restricting their reach and income. The rise of e-commerce platforms like Etsy and Amazon Karigar, as well as India-specific portals such as Craftsvilla and

Jaypore, has dismantled these barriers. Now, artisans in remote villages can list their handwoven textiles, pottery, jewellery and woodwork online, reaching a global audience. This direct-to-consumer approach not only increases earnings but also sustains craft techniques by fueling demand for genuine handmade products. Moreover, greater visibility draws in younger consumers who prioritize sustainability and cultural heritage, aligning artisan crafts with the global trend toward ethical consumption.

Figure: Reviving Indian crafts through Tech and Tradition

Social media: Storytelling and Community Building

To boost sales, social media platforms like Instagram, Facebook and WhatsApp are transforming how artisans communicate the stories behind their crafts. These digital channels allow artisans and cooperatives to share behind-the-scenes glimpses, revealing the demanding processes and cultural significance woven into each piece. Their storytelling fosters deep emotional connections between creators and buyers, helping cultivate loyal customer communities who appreciate the artisan's journey. Social media also acts as a dynamic community hub, where artisans exchange technical knowledge, collaborate on creative innovations and collectively respond to challenges such as supply chain disruptions or shifts in market demand.

Virtual Reality Archives: Preserving Heritage in Immersive Ways

Preserving intangible cultural heritage presents unique challenges, especially since elder artisan's risk losing treasured techniques passed down through generations without proper documentation. To address this, India is embracing virtual reality (VR) and digital archiving. Several Indian initiatives are creating immersive VR archives that meticulously document craft processes, capturing artisans' hand movements, loom mechanics and traditional dyeing techniques through 3D video and interactive modules. These digital repositories transform into invaluable educational tools, allowing future generations to explore ancient craft knowledge even as their lifestyles change. By facilitating virtual apprenticeships, VR enables young artisans to distantly learn traditional crafts, thereby preserving the lineage of techniques while inspiring innovation within established cultural frameworks.

Blockchain Certification: Guaranteeing Authenticity and Fair Trade

A major challenge in the handicrafts market is the buildup of fake goods, which undermine consumer trust and negatively impact genuine artisans. Blockchain technology offers a strong solution with tamper-proof digital certificates of authenticity. Provenance tracking by embedding data such as the artisan's identity, craft origin and production date into a secure blockchain ledger, each piece becomes traceable. Consumers can verify its authenticity instantly via a QR code or NFC scan. Protecting artisans and pricing, this transparency guard's artisans' intellectual property, supports premium pricing and promotes fair trade by clearly linking the product to its creator. Direct compensation via smart contracts, blockchain-enabled payment systems through smart contracts automatically release funds to the artisan upon verification of delivery or sale milestones, ensuring timely and direct compensation while minimizing exploitation by intermediaries.

Empowering Artisan Communities for a Sustainable Future

The harmony between traditional craftsmanship and modern technology signals a transformative era for India's artisan communities. Digital tools do not replace the handmade essence of these crafts; rather, they increase their reach and value, helping artisans adapt to today's economy. Digital literacy and infrastructure support, the Digital Empowerment Foundation (DEF) works across handloom clusters such as Chanderi, Nuapatna, Barabanki and Trichy to promote ICT tools, CAD/CAM design training and social media/e-commerce skills, boosting both design innovation and marketing reach. Targeted skill-upgrading programs: Initiatives by the Nasscom Foundation and L&T Technology Services have digitally upskilled nearly 900 rural women artisans, teaching them smart phone use, online selling, digital payment and social commerce, which has enhanced their business reach and income. National Digital India strategy, through schemes like PMGDISHA, Common Service Centres and partnerships such as Internet Saathi and Google's Digital Unlocked, millions in rural India gain access to digital skills, internet tools, and e-governance services, enabling artisans to sell online, access support schemes and manage their enterprises more effectively. Public-private and NGO collaboration like Governments, NGOs and tech companies, are joining forces to build the necessary digital ecosystem from training and connectivity to platform integration, ensuring these historic crafts thrive in global markets.

Conclusion

The fusion of India's rich artisanal heritage with modern digital technologies showcases how innovation can empower tradition rather than replace it. By leveraging e-commerce platforms, social media, VR archives and blockchain certifications, we are not just preserving ancient crafts; we're rewriting their story. These tools have transformed fragile cultural antiques into thriving symbols of sustainable, global entrepreneurship. In this digital renaissance, traditional craftsmanship is not sidelined; it's celebrated and enhanced, ensuring the handmade heart beats more vibrantly than ever and timeless beauty reaches a global stage, all powered by the innovative drive.

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PLANT–MICROBE INTERACTIONS IN IRON ACQUISITION AND METABOLISM

J. R. Patel[1*], K. J. Patel[2] and P. J. Kandoriya[1]

[1]Department of Agricultural Microbiology, N. M. College of Agriculture, NAU, Navsari, Gujarat, India
[2]Department of Agricultural Microbiology, B. A. College of Agriculture, AAU, Anand, Gujarat, India
*Corresponding Email: jhanavipatel6629@gmail.com

Abstract

Iron is an essential micronutrient required for chlorophyll synthesis, photosynthesis, respiration, enzyme activation and stress tolerance in plants. Its limited bioavailability in soil strongly influences plant growth, crop productivity and even human nutrition. Plants maintain iron homeostasis through tightly regulated uptake, transport, storage and metabolic utilization to avoid both deficiency and toxicity. Iron availability often decreases in soils with high pH, excess phosphorus, calcareous characteristics, low organic matter, or competition with other metals, resulting in chlorosis, reduced biomass and stunted growth. Conversely, excess iron can trigger oxidative stress by generating reactive oxygen species. To acquire iron efficiently, dicots use a reduction-based mechanism (Strategy I), while grasses use a chelation-based mechanism (Strategy II). Beneficial rhizospheric microorganisms further enhance iron acquisition by producing siderophores, organic acids, and growth-promoting compounds. Microbial siderophores—hydroxamates, catecholates and carboxylates—solubilize ferric iron, making it available to both microbes and plants. Understanding these soil–plant–microbe interactions is essential for improving iron nutrition, strengthening plant resilience and advancing sustainable agricultural productivity.

Introduction

Iron is indispensable for plant growth and development. It is required for the synthesis of chlorophyll, the green pigment central to photosynthesis. Beyond that, iron is a key component of the electron transport chains in chloroplasts and mitochondria, supporting photosynthesis and respiration. Many enzymes also depend on iron as a cofactor, enabling essential biochemical reactions. In addition, iron aids plant tolerance to abiotic stresses (e.g. salinity, drought, heavy metals). From a human nutrition perspective, iron in edible plant tissues contributes to dietary iron intake (Fodor, 2024).

However, despite its abundance in the earth's crust, iron is often poorly available to plants due to its tendency to form insoluble compounds under aerobic soil conditions. Thus, the soil availability of iron strongly influences plant growth, crop yields and agricultural success. For example, in regions such as Gujarat and Navsari, monitoring and managing soil iron levels is key to sustaining yields and crop quality. Plants must maintain iron homeostasis: a fine balance among iron uptake, internal transport, storage and utilization, so as to avoid deficiency or toxicity.

In aerobic soils, iron is predominantly present in insoluble ferric (Fe^{3+}) forms, making it difficult for roots to absorb. Plants have evolved specialized mechanisms to mobilize and acquire iron. Once interiorized, iron must be transported to target tissues (e.g. leaves, chloroplasts) for metabolic use, stored safely (e.g. in ferritins or vacuoles) when in excess, and detoxified if reactive. Plants thus operate tightly regulated systems to sense iron status and adjust uptake and internal distribution accordingly (Ning *et al.,* 2023).

Soil conditions strongly influence plant iron dynamics. In alkaline or calcareous soils (pH > 7.5), iron precipitates as hydroxides and oxides, rendering it unavailable. High phosphorus levels can drive formation of insoluble iron–phosphate complexes. In calcareous soils rich in calcium and carbonate, iron precipitation is enhanced, especially under semi-arid conditions. Poor soil aeration (e.g. in waterlogged soils) can hamper root function and iron uptake. Other metal ions (Zn, Mn, Cu, Ni) may compete with iron at uptake sites. Low organic matter also limits natural chelators (humic/fulvic acids) that might help keep iron in soluble forms. Together, these soil constraints challenge the plant's ability to access sufficient iron (Patel and Kumar, 2024).

Causes of Iron Deficiency in Plants

Iron deficiency in plants typically arises from soil and environmental constraints that limit iron availability. Key contributing factors include:

- Alkaline (high pH) soils, which cause iron precipitation and reduce solubility
- Over-application of phosphorus, forming insoluble iron–phosphate complexes
- High calcium and carbonate ($CaCO_3$) content in calcareous soils
- Poor aeration or waterlogging, which impair root uptake
- Competition from other cations (e.g. Zn^{2+}, Cu^{2+}, Mn^{2+}, Ni^{2+})
- Low organic matter, reducing natural chelating agents

Under deficiency, plants exhibit interveinal chlorosis (particularly in young leaves), reduced chlorophyll, weakened root growth and lower biomass accumulation (Molnar *et al.,* 2023).

Iron Toxicity in Plants

Excessive iron uptake can also be detrimental. Free iron catalyzes formation of reactive oxygen species (ROS) via Fenton chemistry, damaging membranes, proteins, and nucleic acids. Iron overload can disrupt redox homeostasis, impair metabolism, and lead to visible symptoms such as bronzing, necrosis, chlorosis, or even plant death. In many cases, excess iron interferes with uptake of other nutrients, causing nutritional imbalances. Crops like rice, tomato, soybean, banana, and coconut are particularly susceptible to iron toxicity, which can significantly reduce productivity (Rout and Sahoo 2023).

Challenges in Plant Iron Uptake

The major challenge for plants is that iron predominantly exists as insoluble Fe^{3+} in aerobic soils. Under neutral or alkaline conditions, its solubility is extremely low, making direct uptake difficult. Additional challenges include competition with other metals, fixation in insoluble compounds (e.g. phosphates), and the absence of chelators in low-organic-matter soils. To overcome these obstacles, plants have developed two distinct iron acquisition strategies:

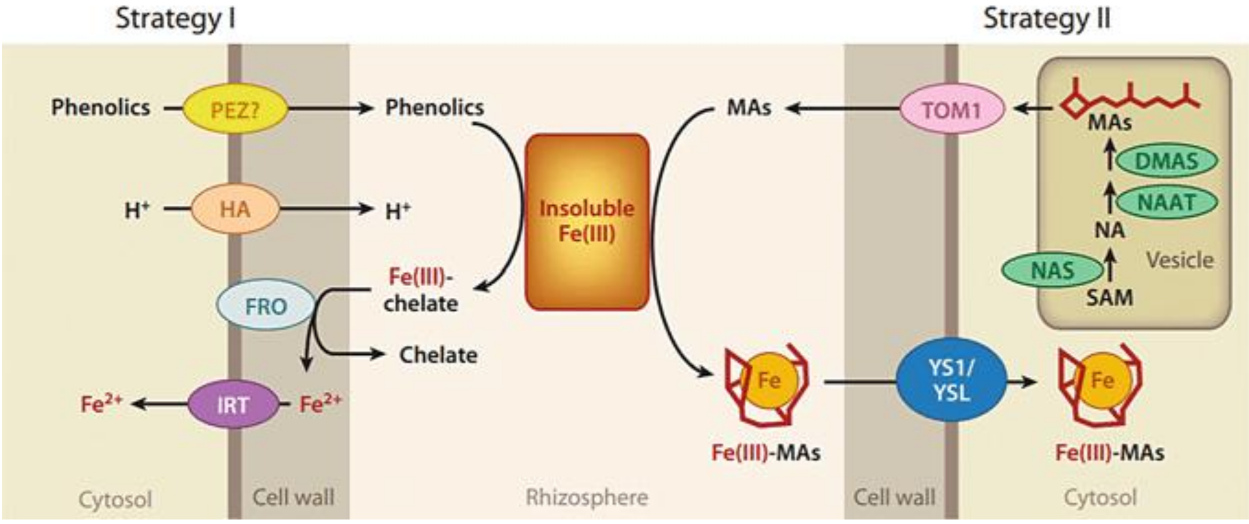
1. **Strategy I (Reduction-based)** — employed by dicots and non-grass monocots
2. **Strategy II (Chelation-based / Phytosiderophore-based)** — employed by grasses (Poaceae)

Strategy I: Reduction-Based Iron Uptake

In Strategy I plants, the root epidermis acidifies the rhizosphere by proton extrusion (via H^+-ATPases), which increases iron solubility. Then, plasma membrane ferric chelate reductases reduce Fe^{3+} to Fe^{2+}, which is transported into root cells via Fe^{2+} transporters (e.g. IRT1). The expression of these transporters and enzymes is regulated by iron status at the transcriptional level.

Strategy II: Chelation-Based Iron Uptake

In Strategy II (found in grasses), roots secrete phytosiderophores (PS) that chelate Fe^{3+} in the rhizosphere to form soluble complexes. These Fe–PS complexes are then taken up via specific transporters (e.g. YS1 or YSL family). Under iron deficiency, secretion of PS and uptake capacity are upregulated, enabling grasses to access iron in otherwise inaccessible forms.



Role of Microbes in Iron Acquisition

Microorganisms in the rhizosphere play a crucial assisting role in plant iron acquisition, especially under iron-limiting conditions. They employ various mechanisms:

Siderophore production: Many bacteria (e.g. *Pseudomonas*, *Azotobacter*, *Rhizobium*) and fungi produce siderophores, which bind ferric iron and solubilize it in chelated form. Plants may indirectly access this iron.

Secretion of organic acids: Microbes can produce organic acids (e.g. citrate, oxalate, malate), lowering rhizosphere pH and solubilizing iron compounds.

Mycorrhizal associations: Arbuscular mycorrhizal fungi enlarge the effective root surface area, facilitate nutrient exchange, and may release acids or ligands to mobilize iron.

Plant growth promotion: Plant Growth-Promoting Rhizobacteria (PGPR) such as *Bacillus* and *Enterobacter* can modulate root architecture via phytohormones, enabling exploration of larger soil volumes for iron.

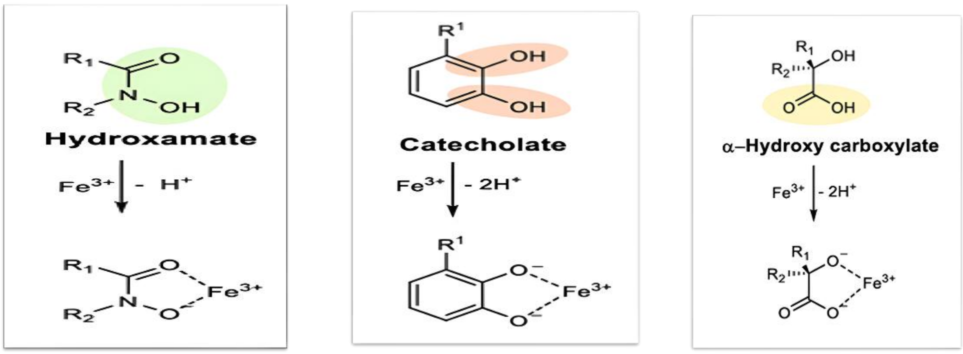
Microbial cooperation and cross-utilization: Some microbes can use siderophores produced by others; and microbial-plant cross-feeding of iron complexes has been documented.

Microbial Siderophores

Siderophores are small, high-affinity iron-chelating molecules secreted under iron-deficient conditions. After chelating Fe^{3+}, the siderophore–iron complex is taken up via specific receptors. The genetic machinery for siderophore biosynthesis and uptake is often organized in operons and tightly regulated based on iron status. Some microbes produce multiple siderophore types; and siderophores from one species can sometimes be exploited by another (Schalk and Mislin 2024).

Siderophores are typically classified into three main structural types:

- **Hydroxamate siderophores**: Contain hydroxamate ligands; form hexadentate complexes. Example: Ferrichrome (produced by fungi).
- **Catecholate (phenolate) siderophores**: Use catechol groups to chelate iron. Example: Enterobactin from *E. coli*.
- **Carboxylate (or mixed carboxylate) siderophores**: Use carboxylate groups or mixed ligand architectures. Example: Rhizobactin from *Rhizobium meliloti*.



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FEEDING THE FUTURE: THE IMPORTANCE OF ARTIFICIAL DIETS IN INSECT REARING

Kavimugilan S[1], Usha[2]*, Akhilesh Kumar Singh[3], Yogendra Kumar Mishra[4]

Department of Entomology, Rani Lakshmi Bai Central Agriculture University,
Jhansi, Uttar Pradesh-284003
*Corresponding Email: ushamauryaentomology@gmail.com

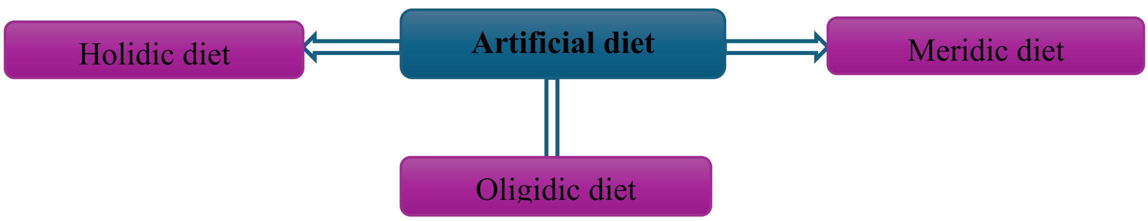
Introduction

Insects are vital components of natural ecosystems and hold immense significance in agriculture, biological research and industrial applications. They function as pollinators, biological control agents, sources of alternative protein, and models for scientific experimentation. As the demand for insects in these sectors grows, so does the need for reliable and scalable insect-rearing techniques. Central to successful mass rearing is the formulation of artificial diets scientifically developed, nutritionally balanced substitutes designed to meet the dietary requirements of diverse insect species efficiently and sustainably.

The Necessity of Artificial Diets:

Traditionally, insect rearing has relied heavily on natural food sources such as host plants or prey insects. However, these methods present several challenges: they are often labor-intensive, seasonally limited, and subject to variability in nutrient composition. Such constraints hinder consistent insect production and complicate experimental reproducibility. Artificial diets overcome these obstacles by providing standardized nutrition that supports optimal growth, survival, and fecundity. The development of artificial diets has revolutionized entomology and applied insect sciences by enabling year-round rearing of insects in controlled environments. This capability is particularly crucial for research laboratories investigating insect physiology, toxicology, and behavior, as well as for commercial programs producing biological control agents and pollinators. Furthermore, with the increasing interest in insects as sustainable protein sources for animal feed and human consumption, artificial diets offer a cost-effective and scalable solution.

Classification of Artificial Diets:



Artificial diets can be classified based on the degree of chemical definition of their components:

1. **Holidic Diets:** These diets are composed exclusively of chemically defined ingredients pure compounds such as amino acids, sugars, vitamins and salts. The complete molecular characterization of each component allows for precise manipulation of nutritional variables. Holidic diets are indispensable in physiological and biochemical research, enabling scientists to elucidate the effects of individual nutrients on insect metabolism and development.

2. **Meridic Diets:** These are semi-defined diets combining chemically characterized components with complex biological materials such as yeast extracts, casein, or plant hydrolysates. While some ingredients remain chemically undefined, meridic diets balance nutritional precision with practicality and cost, making them suitable for large-scale rearing of many insect species.
3. **Oligidic Diets:** These diets contain a substantial proportion of natural ingredients whose chemical compositions are not fully known, such as fresh or processed plant tissues, insect homogenates, or other biological materials. Though less precise, oligidic diets can replicate the nutritional complexity of natural food sources and are often employed when species-specific dietary needs are poorly understood.

An alternative classification considers the inclusion or exclusion of insect-derived ingredients such as hemolymph, cellular extracts, or proteins. Diets incorporating these components better mimic the natural nutritional environment of the insect, potentially improving growth and reproductive outcomes. Conversely, insect-free diets are easier to standardize and scale, particularly for commercial production.

Nutritional Requirements of Insects to prepare artificial diets:
Insect nutritional needs are shaped by their evolutionary adaptations and ecological niches. Understanding these requirements is fundamental to the development of effective artificial diets.

- **Proteins and Nitrogenous Compounds:** Protein is essential for tissue synthesis, enzyme production, and overall growth. Insects require a balanced profile of amino acids, some of which may be essential. Nitrogen sources such as free amino acids, peptides, and nucleotides support these demands. Certain insects also benefit from yeast extracts and casein as rich nitrogen sources to enhance development.
- **Lipids and Fatty Acids:** While many insects synthesize fatty acids from carbohydrates, specific groups like some mosquitoes and lepidopterans require dietary polyunsaturated fatty acids for normal physiological function. Deficiencies can lead to developmental defects, impaired flight, or reproductive failure. Additionally, lipids serve as vital energy reserves and components of cell membranes.
- **Carbohydrates:** Carbohydrates mainly supply energy. Nectarivorous insects, particularly adult lepidopterans, depend heavily on sugars such as sucrose found in plant nectar. These species often possess specialized digestive enzymes enabling efficient carbohydrate assimilation, which is critical for sustaining energy-intensive behaviors like flight.
- **Vitamins and Minerals:** Water-soluble B vitamins (e.g., biotin, folic acid, niacin) act as coenzymes in metabolic pathways. Fat-soluble vitamins such as tocopherol (Vitamin E) contribute to antioxidant defense and reproductive success, while retinol (Vitamin A) is involved in vision and development. Minerals like calcium, magnesium, and trace elements play roles in enzymatic functions and physiological stability.
- **Other Nutritional Factors:** Some insects rely on symbiotic microorganisms to supplement their diet with otherwise unavailable nutrients, highlighting the importance of microbiome interactions in nutritional ecology.

Advantages of Artificial diets in insect rearing:
Artificial diets confer multiple benefits that are transforming insect rearing:

- **Year-Round Rearing Capability:** Insects can be bred continuously without dependence on seasonal host availability, increasing reliability and production volumes.

- **Mass Production Potential:** Enables scaling from small experimental cohorts to industrial quantities required for biological control releases or protein harvest.
- Standardization: Ensures consistent quality and composition, reducing experimental variability and enhancing reproducibility in research.
- **Cost Efficiency:** By using affordable, locally available ingredients and streamlined preparation methods, artificial diets reduce labor and operational costs.
- **Facilitation of Research:** Enables precise studies on nutritional physiology, toxicology, host-pathogen interactions, and genetics by controlling diet composition.

Applications and future prospects:

Artificial diets are integral to several burgeoning fields:

- **Biological Control:** Mass-rearing natural enemies like parasitoids and predators is facilitated by optimized diets, enhancing sustainable pest management.
- **Pollinator Support:** Artificial nutrition sustains populations of vital pollinators, especially when natural floral resources are scarce.
- **Edible Insect Farming:** As insects gain prominence as sustainable protein sources, artificial diets ensure quality and scalability in insect farming enterprises.
- **Scientific Research:** Defined diets permit the study of nutritional ecology, insect metabolism, and the interaction of diet with genetics and microbiota.

Emerging technologies such as metabolomics, microbial engineering and synthetic biology promise to further refine artificial diets, making them species-specific, cost-effective and environmentally sustainable. The development and refinement of artificial diets represent a cornerstone of modern insect rearing. By meeting the intricate nutritional needs of insects, these diets enable efficient, controlled, and scalable insect production. As the demand for insects continues to rise in agriculture, research, and food industries, ongoing innovations in diet formulation will be pivotal in supporting sustainable insect utilization worldwide.

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BIOFUELS: A SUSTAINABLE ALTERNATIVE TO FOSSIL FUELS

Khoob Singh, Akanksha, Khusbu Samal, Shubham Janbandhu and Kaushlendra Nath Pathak

College of Fisheries, Mangalore,
Karnataka Veterinary Animal and Fisheries Sciences University
Bidar, Karnataka-575002.
Acharya Narendra Deva University of Agricultural and Technology,
Kumarganj, Ayodhya, Uttar Pradesh-224229.
Corresponding Email: shubhamjanbandhu18@gmail.com

Abstract

The need for energy around the world is rising daily, which also poses a serious environmental problem. Both the demand and fuel consumption are expected to increase quickly in parallel, and the usage of fossil fuels is having negative environmental effects. One excellent example of renewable energy is biofuels, which can be generated from biological organisms and will ultimately reduce dependency on fossil fuels. Alternative fuels that have the potential to reduce dependence on imports of fossil fuels are liquid biofuels. The idea of biofuel is popular and an alternative for modern fuels. Because they cause no pollution, biofuels are safer to existing fuels. Seaweed, microalgae, and organic waste are used to make biofuels. Because fish wastes are harmless and biodegradable, there is a lot work being done on using them to produce biodiesel. Compared to regular fuel or diesel, biodiesel produces less air pollutants, CO_2, hydrocarbons, and other particles.

Introduction

Global energy demands are rising due to industrialization and population growth, which has led to a number of problems that must be addressed, including pollution of the environment, the depletion of fossil fuels, and the lack of electricity. Environmental preservation and limiting the use of chemicals in fuel generation are the only issues. Eco-friendly methods are crucial for achieving energy demands and overcoming these challenges. Transportation-related greenhouse gas (GHG) emissions have been rising more quickly than those from any other sector. Fossil fuels, which accounted for over 96.3% of all fuel used for transportation in 2018, are a major component of this industry. In addition, transportation accounts for 23% of all energy-related CO_2 emissions and 15% of global GHG emissions. Biofuels are widely seen as viable alternative transportation fuels that may reduce dependency on petroleum-based fuels and mitigate the effects of climate change. Biofuels, including biodiesel, bio-oil, ethanol, methane, and methanol, are generally defined as fuels derived from biomass that can be solid, liquid, or gas. The primary producers of biofuels are photosynthetic organisms, such as vascular land plants, micro- and macroalgae, and photosynthetic bacteria. Since the early days of the automobile industry, biofuels have been utilised. For example, Rudolph Diesel used peanut oil to test his first engine since pulverised coal was unsuitable. Biofuels were considered a feasible fuel for transportation until the 1940s, and bioethanol blends like Agrol, Discol, and Monopolin were widely utilised in the USA, Europe, and other countries. Further development of bioethanol ceased after the Second World War as petroleum-derived fuel became cheaper. During the oil crisis in the 1970s, many countries showed renewed interest in production of commercial biofuels, somehow, only Brazil started to produce ethanol at a large scale as part of the National Ethanol Programme 'Proálcool'.

Biological Systems and Technologies for Biofuel Production

Chemicals that have been augmented with energy and produced from a variety of bioresources and live organisms through a range of biological processes and technological advancements are known as biofuels. The two most well-known sources of biofuels for the last few decades are microbial biomass and plants, both of which are friendly to natural environments. Unlike other living sources, plants and algae are able to use solar energy to photosynthesize, or convert atmospheric carbon dioxide into sugars. The production of biofuels has advanced from ancient to the present and is divided into four sequential generations.

First-generation biofuels are mostly made from wheat, barley, corn, oilseeds, and sugarcane potatoes; biodiesel is made from soybean and sunflower. Sugarcane and uncooked corn were fermented with the help of fungal mycelia to make ethanol. Microbes that break down starch, such as *Rhizopus sp*. and *Saccharomyces cerevisiae*, are used to ferment raw corn flour and produce ethanol. In order to produce first-generation biofuels on a large scale, sucrose or starch is first hydrolyzed by enzymes in an industrial processing system to produce bioethanol. The production of bioethanol from readily available crops, waste wood residues, organic waste materials, and forest dregs is the general term for second-generation biofuels, because microalgae and microorganisms develop quickly and have the capacity to fix CO_2, they are essential for the metabolism of cellulolytic bacteria and the production of biodiesel. Biofuel of the fourth generation is produced by metabolic engineering microalgae by using post genome technology.

Hydrogen production

Around the world, biohydrogen production has begun utilizing various microbial groups. Actinobacteria, Firmicutes, Bacteroidetes, and other phylum and classes include microbes that can produce H_2. The enzyme complex known as hydrogenase or nitrogenase is essential to the generation of H_2. Both prokaryotic and eukaryotic species' processes for producing hydrogen are regulated by these enzymes. Green algae are the most effective at producing biohydrogen through a variety of methods.

Methane/Biogas Production

Hydrolysis, acidogenesis, dehydrogenation, and methanogenesis are the four critical processes in the creation of biomethane. The hydrolysis process, which is the initial stage of producing biomethane or biogas, depends on the molecular structure of the source material, including lignocelluloses, proteins, lipids, and carbohydrates. Fermenting bacteria (FB), including Bacteriocides, Clostridium, and Bifidobacteria, hydrolyze complex biopolymers (lipids, proteins, and carbohydrates) into soluble organic molecules (fatty acids, sugar, and amino acids). Using various fermentative bacteria, the biohydrogen, carbon dioxide, and acetate are formed from soluble organic molecules in the two subsequent stages, known as acidogenesis and acetogenesis.

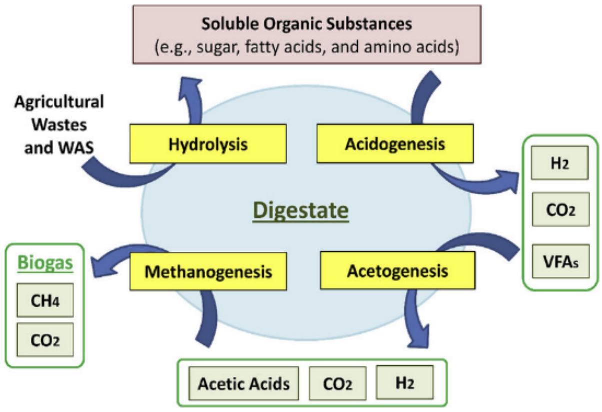

Fig.: Process-wise stages of biogas production Source: (Pan *et al.,* 2021)

Agricultural Waste

Waste production is growing in both volume and variety as the world's population continues to grow. Consequently, it is now difficult to get rid of this expanding garbage. Trash disposal requires energy that is not economically feasible. It has been estimated that 5% of biomass energy is produced from agricultural waste (Deshmukh et al., 2008). Agricultural biomass is composed of the food-based components of crops, such as beets, corn, fruits, and sugarcane, while the non-food-based components include cobs of maize stover, leaves, orchard trimmings, rice husk, rice straw, and stalks (Sims, 2004). The primary constituents of agricultural waste are essentially lignin, ash, cellulose and hemicellulose.

Microalgae

In general, the alkaline pre-treatment method proved to be a promising choice for the production of bioethanol. Algae are diverse groups of aquatic organisms that can conduct photosynthesis and efficiently convert solar energy. They are classified into two types based on their size: (a) macroalgae and (b) microalgae. Microalgae are the first known form of life on Earth. They synthesize chemical intermediates and hydrocarbons that can be converted into a variety of fuel options, including alcohols, diesel, methane, and hydrogen. Nowadays, fossil fuels are the primary source of methanol.

Currently, the methanol is mainly produced from fossils. The chemical process used to produce methanol involves three steps: steam reforming, synthesis, and distillation. This process turns natural gas (CH_4, methane) into methanol.

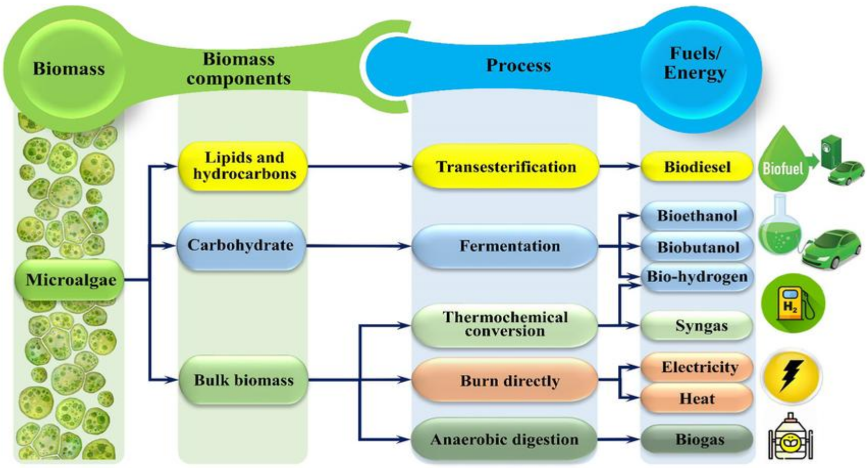

Fig.: Different routes for biofuels/bioenergy production from microalgae (Abo *et al*., 2019)

Bioethanol Production

A liquid biofuel, bioethanol (C_2H_5OH) can be synthesized using a variety of conversion processes with the aid of microorganisms and biomass feedstocks. The amount of bioethanol produced worldwide is continuously rising. Using microbial enzymes (bacterial and fungal), the process of producing bioethanol can be divided into several steps, including the preparation of the feedstock, pretreatment, hydrolysis or saccharification, fermentation using various microbes (bacterial, fungal, and yeast), and distillation and dehydration as the final steps. Kim and Dale (2004) have evaluated the bioethanol production potential of a variety of crops, including barley, corn, oats, rice, sorghum, sugar cane, and wheat, on a global scale. High levels of silica and ash in the substrate also boost the generation of ethanol.

Biofuels from fish wastes

The production of animal feed supplements, aquaculture feed, fishmeal, fish silage, and renewable energy sources like biodiesel and biogas are the most important, practical, and environmentally positive applications of fish waste. Composting for the production of organic fertilizers, the pharmaceutical and cosmetic industries, the production of collagen, fish protein hydrolysate, fish bone extracts, and polyunsaturated fatty acids, and the extraction of commercial and novel enzymes, including proteases, from natural colours. Fish wastes rich in omega-3 fatty acids are unavailable since they are essential to the pharmaceutical industry. Additionally, stay away from very dried fish. Biogas (bio-methane) and biodiesel are two important types of biofuels made from waste.

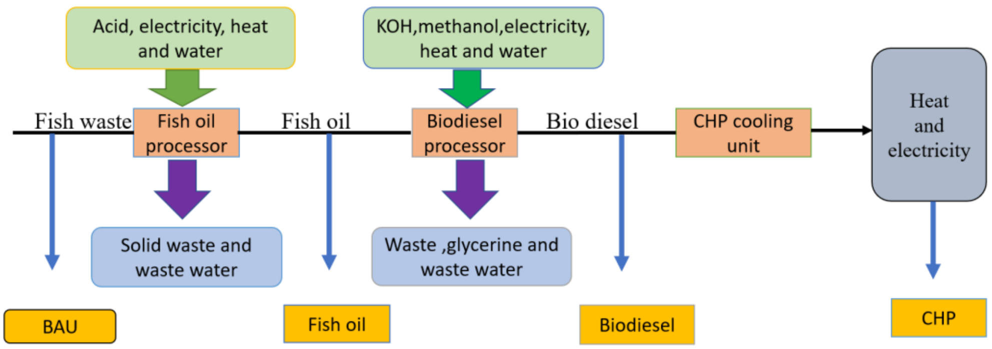

Fig.: The process flowchart of biofuel production from fish wastes (courtesy ENERFISH Vietnam).

Biodiesel production

There are several ways to extract biodiesel, including transesterification, transesterification using an alkaline catalyst, two-stage reaction procedures, separation processes, microwave-assisted lipid extraction, and traditional techniques like wet and dry rendering.

Biogas production

While transesterification will be the main method for creating biodiesel, other methods will also be used to create diverse byproducts. The process stated above relies on the production of glycerin as a byproduct in addition to heat and energy. In order to produce a by-product such as biogas, anaerobic digestion must be carried out in between process steps. Biogas can be generated from oil-free fish waste (cake). Sewage sludge and manure could be mixed with fish waste. It is possible to turn the digestate into fertilizer

Anaerobic digestion

The process by which microorganisms break down biodegradable materials without the presence of air is known as anaerobic digestion. After anaerobic digestion, digestate with various nutrients and biogas with CH_4 (50–75%), CO_2 (25–45%), and by-products like H_2S (<1%) are the end products. There are four steps in the breakdown process:

Methanogenesis

Acetogenesis products are converted by methanogenic bacteria into CO_2 and methane. These bacteria are the most susceptible to the operating parameters (temperature, pH, and residence duration). A by-product called methane is used to make biogas. Because these gases are needed to replace liquefied petroleum, this method is also more profitable.

Co-digestion

A common approach for using hazardous waste to produce biogas is the anaerobic digestion of biomass. Although it is generally not widely used, anaerobic digestion of fish waste is also feasible. While fish waste has a lot of potential as a source of very valuable organic carbon for the synthesis of methane, it also has drawbacks, such as a high nitrogen and ammonia concentration. In order to effectively produce biogas, co-digestion involves blending fish waste with sludge or other wastes. The balance of several factors, including macro and micronutrients, the C:N ratio, pH, hazardous chemicals, and dry matter, is the primary concern in co-digestion. Using the Automatic Methane Potential Test System (AMTPS II), the procedure is performed at a mesophilic temperature. This apparatus uses batch testing to automatically measure methane production.

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BIOLOGICAL CONTROL OF INSECT PESTS IN AGRICULTURE

Aman Kumar[1*] and Radheshyam Ramkrishna Dhole[2]

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Sasaram, Rohtas – 821305
[2]Assistant Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Sasaram, Rohtas – 821305
***Corrosponding Email:** akamankumar957040@gmail.com

Abstract

Biological control has emerged as a sustainable and eco-friendly alternative to chemical pest management in modern agriculture. It involves the deliberate use of living organisms such as predators, parasitoids, pathogens, and antagonists to suppress insect pest populations. With the global emphasis on food safety, environmental conservation, and reduced chemical residues, biological control systems are gaining unprecedented attention. This article provides a comprehensive overview of the concept, its historical background, key features, strategies and methods used for biological pest control, its practical applications in crop ecosystems, and the future prospects of integrating biological control into global agricultural production. The discussion highlights how biological control can form the backbone of integrated pest management (IPM) and ensure sustainable agricultural productivity.

Key words: biological control, insect pests, predator, parasitoids, natural enemy etc.

Background

Agriculture has forever been challenged by insect pests that cause direct and indirect damage to crops, leading to substantial economic losses. Traditionally, synthetic pesticides remained the primary tool for pest suppression due to their quick action and cost efficiency. However, excessive and indiscriminate pesticide use resulted in multiple challenges such as pesticide resistance, destruction of beneficial organisms, environmental contamination, biomagnification, and adverse impacts on human and animal health.

Historically, biological control practices began much earlier than chemical control. In the 4th century AD, Chinese citrus growers used predatory ants to suppress pests in orchards. The modern era of biological control started in the late 19th century when the Vedalia beetle (*Rodolia cardinalis)* was successfully introduced in California to suppress cottony cushion scale on citrus. The increasing demand for organic and residue-free agricultural production has revived interest in biological control as a sustainable approach.

Biological control aims not to eradicate pests but to regulate them within economically safe limits, enabling crop protection without disturbing ecological balance. It is a cornerstone of Integrated Pest Management (IPM), complementing cultural, mechanical, and host-plant resistance strategies.

Key Features of Biological Control

The significance of biological control stems from several distinctive benefits:

1. **Environmentally Safe and Sustainable**
   Biological control avoids chemical residues, thus conserving biodiversity, improving soil biology, and preventing ecosystem disruption.

2. **Self-Perpetuating Mechanism**
   Many biological agents continue to multiply and sustain pest suppression without repeated intervention.
3. **Economic Feasibility**
   Although the initial cost of research or introduction may be high, long-term usage is cost-effective due to reduced chemical inputs and minimal labor.
4. **Compatibility with Other Pest Management Technologies**
   Biological control works harmoniously with IPM systems including cultural practices, pheromones, and resistant varieties.
5. **Prevention of Pesticide Resistance**
   Using natural enemies reduces selection pressure on pests, thereby lowering the likelihood of resistance development.
6. **Long-Term Pest Regulation**
   Instead of temporary pest elimination, biological control ensures long-term pest population regulation.

Methods and Applications of Biological Pest Control

Biological control methods can be broadly classified into natural, conservation, classical (importation), augmentative (inoculative/inundative), and microbial control. Their practical application varies with crop type, pest species, and agro-ecosystem.

1. Classical (Importation) Biological Control

This involves the introduction of natural enemies from the pest's native habitat into a new region where the pest has become invasive.
Example: Introduction of *Rodolia cardinalis* to control cottony cushion scale.

Application: Most suitable for perennial crops such as orchards and plantations.

2. Augmentative Biological Control

Natural enemies are mass-reared in laboratories and released into agricultural fields to boost their population.

Inoculative releases: Small numbers released periodically to establish long-term control.

Inundative releases: Large numbers released for immediate suppression.

Examples of beneficial organisms

Type	Examples
Predators	Ladybird beetles, lacewings, predatory mites
Parasitoids	*Trichogramma chilonis*, *Bracon hebetor*, *Aphidius colemani*
Entomopathogenic fungi	*Beauveria bassiana*, *Metarhizium anisopliae*
Bacteria	*Bacillus thuringiensis* (*Bt*)
Nematodes	*Steinernema* and *Heterorhabditis* species

3. Conservation Biological Control

This approach focuses on protecting and enhancing existing populations of natural enemies through:

- Avoidance of broad-spectrum pesticides
- Habitat manipulation with flowering strips, cover crops, and refugia

- Providing food resources such as nectar and pollen

Example: Maintenance of hedgerows provides habitats for predatory insects and birds that suppress pests.

4. Microbial Control

Microorganisms infect and kill insect pests either through toxins or parasitism.
Bacteria: Bacillus thuringiensis used against lepidopteran larvae

- Viruses: Nucleopolyhedrovirus (NPV) effective against Helicoverpa armigera
- Fungi: Beauveria bassiana infecting a wide range of insect
- Protozoa & Nematodes: Used in soil pest management

These agents are made available commercially as biopesticide formulations.

Practical Applications in Agriculture

Biological control has shown great success across crop sectors

Crop	Target pests	Biological agents
Cotton	Bollworms	*Trichogramma* spp., NPV
Rice	Stem borers, leaf folder	*Trichogramma japonicum*, spiders
Vegetable crops	Aphids, whiteflies, caterpillars	Ladybird beetles, *Bt*, parasitoids
Sugarcane	Early shoot borer, internode borer	*Trichogramma chilonis*
Fruit orchards	Mites, scales, mealybugs	Predatory mites, *Cryptolaemus* beetle

Additionally, biocontrol is now widely integrated into organic farming and protected cultivation systems such as polyhouses and greenhouses.

Conclusion

Biological control of insect pests has proven to be a sustainable, eco-friendly, and profitable approach to crop protection in agriculture. It minimizes dependency on harmful chemical pesticides while protecting biodiversity and safeguarding human and environmental health. Although biological control agents may act slower compared to chemical pesticides, their long-term effects, self-regulating nature, and ecological benefits make them essential elements of future agriculture. The integration of biological control with other components of Integrated Pest Management enhances reliability and field success.

Future Strategy

To expand the use of biological control in global agriculture, the following strategies are necessary:

- Establishment of mass-production facilities for natural enemies and microbial biopesticides at affordable prices.
- Strengthening extension and farmer education to increase awareness and adoption.
- Research on climate-resilient biocontrol agents suitable for diverse agro-climatic zones.
- Development of precision-delivery technologies such as drones for parasitoid and microbial release.
- Government policies and subsidies promoting biopesticide use over chemical pesticides.
- Digital pest monitoring and forecasting systems to coordinate timely release of biocontrol organisms.
- Public–private partnerships for commercialization and large-scale implementation.

Adopting these strategies can pave the way for environmentally responsible crop protection and sustainable food security.

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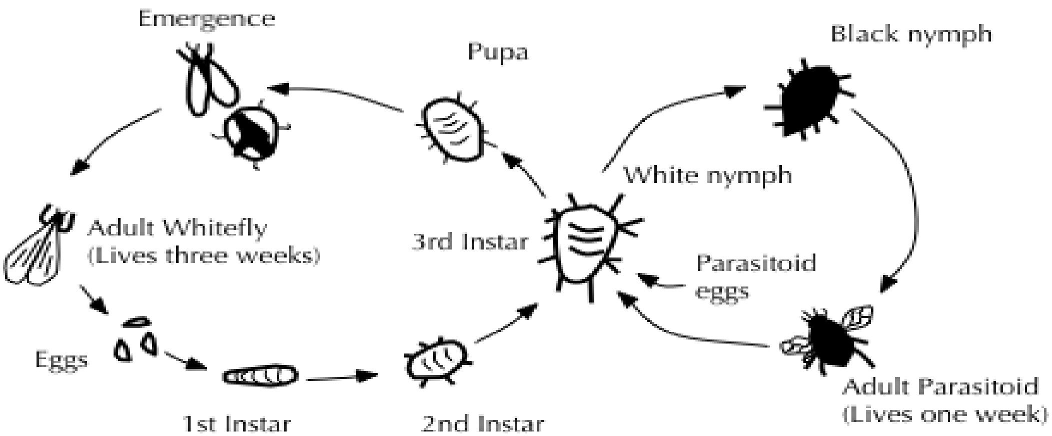

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CACTUS PEAR - THE GREEN GOLD OF THE DESERT

Amrutha A[1*], Meera Mohan N[2] and Sonia N. S.[3]

[1]PG scholar, Department of Horticulture, College of Agriculture, Padannakkad, Kasaragod, Kerala-671314
[2]Assistant Professor, Department of Horticulture, College of Agriculture, Padannakkad, Kasaragod, Kerala-671314
[3]Assistant professor, Department of Horticulture, College of Agriculture, Padannakkad, Kasaragod, Kerala-671314
*Corresponding Email: amruthaanair4@gmail.com

Introduction

Cactus pear (*Opuntia ficus-indica* (L) Mill.), commonly known as prickly pear, Indian fig, or Barbary fig, is native to Mexico and distributed in arid and semi-arid regions of the world. This hardy fruit plant is widely cultivated in the arid and semi-arid regions of India, mainly in Rajasthan, Gujarat, and certain parts of Odisha, Uttar Pradesh, Madhya Pradesh and Karnataka. It belongs to the cactus family (Cactaceae), and is well known for its remarkable ability to survive with minimal water. The plant's distinctive, flat, fleshy pads, known as cladodes or nopales, serve as modified stems that efficiently store water, allowing the cactus to remain productive and thrive in extreme heat and limited moisture conditions.

Far from being merely an ornamental desert species, cactus pear is a versatile, multi-purpose crop valued for both its edible pads and vibrant fruits. The fruits, known as tunas, are oval to elongated, resembling an apple or a pear. They are fleshy berries, varying in colour from white, yellow, and green to deep red and purple. The fruit contains about 84–90% water and 10–15% sugars. Its inner pulp is less seedy and rich in nutrients, while the young, tender pads are consumed as vegetable, appreciated for their crisp texture and slightly tart flavour.

Drought Survival Mechanisms in Cactus Pear

The wide distribution of the genus *Opuntia* is mainly attributed to its unique adaptations to water scarcity and intense sunlight. These include the use of Crassulacean Acid Metabolism (CAM), reduced leaf structures, thick cuticular wax coatings on cladodes and fruits, and a strong regenerative ability through root calluses, pads, fruits, seeds, tissue culture, and grafting. Together, these characteristics enable *Opuntia* to grow continuously and remain evergreen even under harsh environmental conditions.

These adaptations significantly reduce water loss through transpiration, allowing the plant to withstand prolonged dry periods. In drought conditions, the pads slowly shrink as they utilise stored water, which also reduces the surface area exposed to sunlight and helps prevent dehydration. The spines and tiny glochids not only protect the plant from herbivores but also provide shade, thereby further reducing moisture loss. During extreme drought, the fine feeder roots may die back to conserve internal water reserves; however, they regenerate rapidly once moisture returns, enabling quick recovery and continued growth.

Cactus Pear Utilisation

The harvesting season of *Opuntia* species varies geographically, from April to August in the Americas and from November to December in the Mediterranean region. In local markets, the fruits are sold either peeled or unpeeled. In India, cactus pear fruits and pads are gaining popularity, priced at around ₹100–200 per kilogram, and are utilised in food, animal feed, cosmetics, and traditional medicine.

1. Culinary Uses (Food and Beverage)

The tender nopales are often grilled, sauteed, or diced and incorporated into various dishes. They serve as a low-calorie, high-fibre vegetable that adds both nutritional and functional benefits to the diet.

The fruit pulp is equally versatile and processed into value-added products such as juices, jams, jellies, candies, and syrups. Its naturally sweet-tart flavour, coupled with antioxidant-rich betalains, enhances its appeal as a healthy and colourful ingredient in modern cuisine, yoghurt, and ice cream.

2. Agricultural and Environmental Uses (Sustainability)

Beyond its dietary uses, cactus pear holds immense potential in sustainable agriculture and environmental conservation. The plant is increasingly used as livestock fodder, particularly in arid and drought-prone areas. The pads contain up to 90% water, offering critical hydration and essential nutrients to animals during dry seasons when conventional fodder is unavailable.

Cactus pear also contributes to soil restoration and desertification control. Its extensive root system and water retention properties improve soil structure, prevent erosion, and enhance the fertility of degraded lands. Cultivating cactus pear helps maintain ecological balance and supports climate-resilient farming systems.

3. Health and Medicinal Benefits (Superfood Status)

The cactus pear is a nutritionally rich fruit, providing around 14% of the daily value (DV) for dietary fibre, 23% DV for vitamin C, and 21% DV for magnesium, making it a valuable component of a healthy diet (Cota-Sanchez,2016). Its mineral content is also notable, offering significant levels of calcium, magnesium, potassium, and phosphorus, all of which are essential for bone strength, muscle function, and cellular activities.

The fruit contains 180–300 mg of ascorbic acid (vitamin C) per kilogram of fresh weight, contributing to its strong antioxidant potential. In addition to vitamin C, cactus pear also supplies vitamin E, vitamin K, and beta-carotenes, which support immune function, skin health, and protection against oxidative stress. Moreover, cactus pear is abundant in antioxidants, including flavonoids, betalains, carotenoids, quercetin, and pectin. These compounds help neutralise harmful free radicals and have been linked to anti-inflammatory, cardio-protective, and anti-ageing effects. Regular consumption can contribute to reduced oxidative stress, improved digestion, stronger immunity, and better overall metabolic health. Cactus pear is also a source of important essential and non-essential amino acids such as alanine, arginine, and asparagine. The seeds further enhance the fruit's nutritional value, being rich in minerals and sulphur-containing amino acids.

In summary, the wide range of nutrients and bioactive compounds in cactus pear underscores its value as a functional and nutraceutical ingredient. Consuming the whole fruit, including both pulp and seeds, ensures maximum intake of these beneficial components, promoting overall health and well-being.

Conclusion

Cactus pear represents a model crop for climate-resilient and sustainable agriculture. Its remarkable drought tolerance, high nutritional value, and ecological benefits make it an ideal plant for cultivation in arid and semi-arid regions. By offering food, fodder, and health-promoting compounds, it supports both human and environmental well-being. Promoting its wider cultivation and utilisation can play a crucial role in enhancing food security, income generation, and ecosystem stability in the face of global climate change.

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CLIMATE-SMART AGRICULTURE: INTEGRATING SCIENCE, SOIL, AND SUSTAINABILITY

Anitrosa Innazent

Agronomy specialist, Feathersoft -Thinkbio ai company.
Corresponding Email: anitrosa@gmail.com

Introduction: Farming in a Warming World

Climate change is no longer a distant scientific theory it is a reality unfolding in India's fields every single day. Unpredictable monsoons, severe droughts, record heat waves, pest outbreaks, and diminishing soil health are reshaping the agricultural landscape. As agriculture depends heavily on climate, farmers bear the brunt of these changes. Yet, amid these challenges rises a powerful solution: Climate-Smart Agriculture (CSA).

Climate-Smart Agriculture:

Climate-Smart Agriculture, an approach promoted globally by the FAO, rests on three pillars:

1. Sustainably increasing agricultural productivity
2. Enhancing resilience (adaptation)
3. Reducing greenhouse gas emissions (mitigation)

CSA is not a single technology; instead, it is a bundle of practices, from improving soil organic matter and efficient irrigation to promoting renewable energy and climate-resilient seed varieties.

India Needs Climate-Smart Agriculture

India is one of the most climate-vulnerable nations. Agriculture, which supports over 50% of the population, faces multiple threats:

- Monsoon variability affecting sowing cycles
- Water scarcity, especially in peninsular India
- Heat stress on crops like wheat and vegetables
- More pests and diseases due to rising temperatures
- Declining soil fertility and organic matter
- Frequent droughts and floods

With nearly 86% small and marginal farmers, India must adopt climate-adaptive strategies that are *affordable, scalable, and sustainable*.

Building Resilience from the Ground Up: Healthy Soils

Soil Health is Climate Health

Healthy soils act like a sponge absorbing water, storing carbon, enhancing biodiversity, and boosting yields. But decades of chemical overuse, residue burning, erosion, and loss of organic matter have weakened Indian soils.

1. Organic Matter Enrichment

- Composting
- Farmyard manure (FYM)
- Green manuring (e.g., sunnhemp, dhaincha)
- Biochar addition

Organic matter increases water retention, reduces temperature stress, and improves nutrient availability.

2. Conservation Agriculture
- Minimum tillage
- Permanent soil cover
- Crop rotation and diversification

These practices lower fuel use, reduce emissions, and increase soil carbon.

3. Microbial and Biological Enhancers
- Biofertilizers (Rhizobium, Azospirillum, PSB)
- Mycorrhizal fungi
- Trichoderma and biocontrol agents

They help plants tolerate drought, resist diseases, and access nutrients more efficiently.

Smart Water Management: Adapting to Scarcity
Water will define the future of agriculture. Climate-smart irrigation techniques ensure every drop counts.

1. Micro-Irrigation (Drip & Sprinkler)
- Saves 30–70% water
- Increases fertilizer efficiency through **fertigation**

2. Rainwater Harvesting & Farm Ponds
Farm ponds help farmers store monsoon water for dry months, stabilizing livelihoods.

3. Sensor-Based Irrigation
Using soil moisture sensors or tensiometers ensures irrigation only when the crop actually needs it.

4. Mulching for Moisture Retention
Organic mulches (leaves, straw) and plastic mulches reduce evaporation drastically.

Climate-Resilient Seeds: Science Meets Sustainability
Seed resilience is the first line of defence against climate stress.

Types of climate-smart varieties:
- Drought-tolerant millets, pigeon pea, groundnut
- Flood-tolerant rice varieties
- Heat-tolerant wheat and tomato
- Salt-tolerant rice for coastal regions
- Short-duration and early-maturing hybrids

Indian research institutions like ICAR, IARI, CRRI, IIMR, and state agricultural universities are developing advanced climate-resilient cultivars.

Diversified Farming Systems: Reducing Risk, Increasing Stability
Climate-smart agriculture encourages diversification to reduce climate risks.

1. Integrated Farming Systems (IFS)
A blend of crops, livestock, fishery, horticulture, and beekeeping provides:
- multiple income streams

- better nutrient recycling
- increased resilience

2. Crop Diversification
Shifting from water-intensive crops (like paddy) to millets, pulses, and oilseeds enhances soil health and lowers water demand.

3. Agroforestry
Trees like neem, moringa, gliricidia, bamboo, and fruit crops in farms:

- Sequester carbon
- Reduce heat stress
- Protect soil
- Offer additional income

4. Urban and Peri-Urban Farming
Rooftop gardens and hydroponics support local food systems and reduce carbon transport footprints.

Technology and Climate Smartness: A Powerful Partnership
India's digital agriculture revolution is accelerating CSA adoption.

1. Remote Sensing & GIS
Used to:

- Monitor crop stress
- Map soil carbon
- Predict drought
- Guide advisory services

2. Drones

- Precision spraying
- Nutrient mapping
- Disease hotspot identification

3. AI & Mobile Advisory Apps
Smartphone advisory tools provide climate forecasts, best planting dates, and pest/disease alerts.

4. Solar-Powered Technologies

- Solar pumps
- Solar dryers
- Solar cold storage

These reduce emissions and improve energy access for farmers.

Challenges in Scaling CSA
Despite its benefits, India faces hurdles:

- limited awareness among small farmers
- fragmented landholdings
- upfront cost for micro-irrigation or solar pumps
- need for stronger extension services
- lack of localized climate models
- low availability of resilient seeds in remote areas

The solution lies in **customized local interventions**, targeted subsidies, and strengthening farmer collectives.

Government and Institutional Support

India is actively pushing CSA through:

- National Mission for Sustainable Agriculture (NMSA)
- Pradhan Mantri Krishi Sinchai Yojana (PMKSY)
- Paramparagat Krishi Vikas Yojana (PKVY) for organic farming
- Soil Health Card Scheme
- National Innovations in Climate Resilient Agriculture (NICRA) by ICAR
- Krishi Vigyan Kendras (KVKs) for farmer training
- PM-KUSUM for solar pumps

Conclusion: A Climate-Smart Future Begins in the Soil

Climate-Smart Agriculture is not a luxury it is a necessity. By integrating scientific innovations, soil health principles, and sustainable practices, CSA empowers farmers to thrive despite climate uncertainty.

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MANAGEMENT OF STORAGE GRAIN PESTS OF RICE (ORYZA SATIVA)

Roushani Singh1* and Radheshyam Dhole2

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Rohtas, Bihar- 821305
[2]Assistant Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Rohtas, Bihar- 821305
*Corresponding Email: roushanisingh147@gmail.com

Abstract
Rice is a critical staple crop for over half of the world's population, and its safe storage after harvest is essential for ensuring food security and maintaining grain quality. However, significant post-harvest losses occur due to the infestation of storage grain pests such as the rice weevil (*Sitophilus oryzae*), Lesser grain borer (*Rhyzopertha dominica*), Khapra beetle (*Trogoderma granarium*), and the rice moth (*Corcyra cephalonica*). These pests cause quantitative losses through direct consumption of grain and qualitative damage by contaminating and deteriorating grain quality. Effective management therefore requires a comprehensive and integrated approach that emphasizes sanitation, proper drying, structural management, biological control, and judicious use of chemical fumigation. This article reviews major pest challenges in stored rice and discusses established and emerging strategies for effective management. Future prospects such as hermetic storage, biological alternatives, and digital grain-monitoring systems are also explored, offering pathways toward sustainable and eco-friendly pest control.

Key words- Rice, Storage pest, Management, Post harvest loss etc.

Introduction

Rice is cultivated on millions of hectares globally and stored for extended periods to ensure year-round supply. The post-harvest stage, however, is one of the most vulnerable phases due to potential losses by insects, rodents, fungi, and mites. Storage pests thrive particularly in tropical and subtropical regions where high temperature and humidity favor rapid population growth. Post-harvest losses of stored grains—including rice—can range from 10% to 30% in traditional storage systems, posing a major threat to food security and farm income.

The most destructive storage pests of rice include primary pests that attack whole grains (e.g., *Sitophilus oryzae*, *R. dominica*) and secondary pests that feed on broken grains and debris (e.g., *Tribolium castaneum* and *Trogoderma granarium*). These pests not only reduce the weight of stored rice but also cause discoloration, increase moisture levels, introduce microorganisms, and reduce market value.

Given the limitations of conventional chemical control—such as resistance, environmental impact, and residue concerns—modern storage grain pest management emphasizes Integrated Pest Management (IPM). This approach combines preventive measures, improved storage structures, physical and biological tools, and safe chemical interventions to minimize losses while ensuring sustainability.

Methods of Managing Storage Grain Pests of Rice

1. Preventive Measures : Prevention is the most critical and economical strategy in storage pest management. Measures taken prior to storage effectively reduce the likelihood of pest introduction and establishment.

a. Cleaning and Sanitation

- Remove all old grain residues, dust, and debris from storage facilities.
- Disinfect floors, walls, and storage equipment using recommended chemicals, lime wash, or hot air.
- Maintain proper waste disposal and prevent rodent entry.
- Clean threshers, harvesters, and transport bags to avoid carryover infestation.

Sanitation reduces food sources for secondary pests and disrupts pest breeding sites.

b. Drying of Grains

Moisture content plays a major role in pest development. Rice should be dried to 12–14% moisture for short-term storage and below 12% for long-term storage.

- Sun-drying (spreading grains thinly and stirring regularly) is widely practiced.
- Mechanical dryers provide uniform drying, especially during humid weather.

Lower moisture slows insect reproduction and prevents fungal growth.

c. Use of Improved Storage Structures

Traditional gunny bags and mud bins offer minimal protection. Improved structures include:

- **Metal bins**
- **HDPE/PP bins**
- **Hermetic storage bags** such as PICS and Super Grain bags
- **Concrete silos** and **metal silos**

Hermetic systems deprive insects of oxygen, causing mortality without chemicals.

2. Physical and Mechanical Methods

These methods are safe, residue-free, and increasingly popular in sustainable storage systems.

a. Temperature Management

Insects have specific thermal thresholds.

- **High temperature** (55–60°C for several hours) kills all life stages.
- **Low temperature** (<15°C) slows pest development, while <10°C can immobilize insects.

Heating can be done using solar heaters, steam, or hot air blowers.

b. Aeration and Ventilation

Aeration helps maintain uniform temperature and low humidity within grain masses.

- They reduce hot spots, which otherwise attract pests and mold.
- Modern silos use forced aeration systems with thermostatic control.

c. Mechanical Cleaning and Separation

- Sieves and aspirators remove broken grains and dust.
- Removing damaged grains eliminates breeding substrates for secondary pests.

This method is especially important before long-term storage.

3. Biological Control

Biological methods leverage natural enemies and plant-derived products to suppress pest populations.

a. Use of Natural Enemies

- *Trichogramma spp.* (egg parasitoids) helps reduce moth populations.
- Predators such as *Xylocoris flavipes* feed on larvae of stored-grain beetles.

Although biological control in bulk storage is still limited, research continues to improve its application.

b. Botanicals and Essential Oils

Many plant products have insecticidal, antifeedant, or repellent properties:

- Neem oil and neem seed kernel extract (NSKE)
- Eucalyptus, clove, turmeric, mint, and black pepper powders
- Sweet flag (*Acorus calamus*) powder

Botanicals are biodegradable, safe, and preferred for household-level storage.

4. Chemical Control

Chemical control remains a widely used method for large warehouses and commercial storage, but must be practiced responsibly.

a. Structural Insecticides

Empty storages can be treated with residual insecticides such as:

- Malathion
- Deltamethrin
- Cypermethrin

These formulations should not be applied directly to stored grains unless specifically approved.

b. Fumigation

Fumigation is essential for managing heavy infestations in bulk storage.

- Aluminum phosphide (PH_3) is the most common fumigant.
- Must be applied only by trained personnel following safety protocols.
- Requires gas-tight conditions to be effective. Fumigation kills adults, larvae, pupae, and eggs.

c. Grain Protectants

Certain chemicals, such as synthetic pyrethroids, can be applied as grain protectants for long-term storage. However, many countries regulate their use strictly to avoid residues in food grains.

5. Integrated Pest Management (IPM) Approach

IPM integrates multiple pest management elements for long-term and eco-friendly control.
Key components include:

- Regular monitoring with pheromone traps, probe traps, and visual inspections.
- Sanitation + moisture management as a foundation.
- Modified atmosphere storage (low oxygen, high CO_2).
- Use of hermetic bags, biopesticides, and botanicals where possible.
- Training and awareness among farmers, warehouse staff, and traders.

IPM reduces reliance on chemicals, lowers costs, and increases sustainability.

Conclusion

Storage grain pests of rice pose serious threats to food security and economic stability. Losses caused by pests can significantly reduce both the quantity and quality of stored rice, affecting consumers and producers alike. Effective management requires a combination of preventive tactics, improved storage practices, physical and biological tools, and careful use of chemical fumigation. Among these, sanitation and moisture control remain the cornerstones of any successful management strategy. A shift toward integrated and environmentally friendly approaches has shown promise in reducing pest pressure and minimizing health hazards. Sustainable, low-cost technologies—especially hermetic storage—have made safe grain storage more accessible to smallholder farmers. Continued adoption of integrated approaches is vital for ensuring the long-term protection of stored rice.

Future Prospects

Future advancements in the management of storage grain pests of rice will emphasize sustainability, technology, and reduced reliance on synthetic chemicals.

1. **Hermetic and Controlled Atmosphere Storage :** Wider use of oxygen-limiting systems will ensure safe, chemical-free protection.
2. **Digitized and IoT-based Monitoring :** Smart sensors for temperature, humidity, carbon dioxide levels, and insect detection are emerging tools in commercial grain storage.
3. **Biopesticides and Microbial Fumigants :** Research on microbial agents such as *Bacillus thuringiensis* and essential-oil-based fumigants offers eco-friendly solutions.
4. **Genetic Resistance in Rice Varieties :** Developing varieties less susceptible to cracking and insect penetration could provide long-term resistance.
5. **Nanotechnology :** Nano-formulations of plant extracts or minerals may enhance protection with minimal residues.
6. **Community Storage Infrastructure :** Shared metal silos and modern storage centers can significantly reduce farmer-level losses in rural areas.

With increasing focus on environmental safety, future pest management will likely rely more on eco-friendly, automated, and precision-based systems, benefiting both producers and consumers.

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COMMUNICATION METHOD IN AGRICULTURAL EXTENSION

Ohaeri, C. V*, Adamu D. A and Orimafo P. K

Research Outreach Department, Nigerian Stored Products Research Institute
Corresponding Email: adamu.davida@gmail.com

Abstract

Communication is a cornerstone of effective agricultural extension, enabling the flow of knowledge, innovations, and feedback between research institutions, extension agents, and farming communities. This study examines the diverse communication methods employed in agricultural extension, situating them within their historical and institutional context. It highlights persistent challenges such as infrastructural constraints, low capacity among agents and farmers, mismatches between methods and audience, poor feedback loops, and cultural or literacy barriers. The article reaffirms key principles for extension communication relevance, clarity, two-way interaction, timeliness, multiplicity of channels, and monitoring. It reviews conventional methods including interpersonal visits, group meetings, mass media, print materials, and visual demonstrations, outlining their strengths and limitations. The article then shifts focus to emerging approaches: mobile messaging, smartphone apps, social media, IVR systems, participatory sensing, remote sensors, and delay-tolerant networks. The prospects of ICTs in extension are discussed, from AI-driven decision support and IoT-based sensing to AR/VR training and data-driven advisory. The article concludes that although ICTs hold vast promise, their success depends on overcoming infrastructural, social, and institutional barriers. Recommendations include capacity building, infrastructure improvement, blended communication strategies, local adaptation, enhanced feedback systems, and policy support.

Keyword: ICT, Extension, Communication, Cooperative, Training

Introduction

Agricultural extension refers to the system of transferring agricultural knowledge, innovations, and practices from research and government agencies to farmers and rural communities, in order to improve productivity, sustainability, and livelihoods. Communication lies at the heart of extension: without effective communication, innovations cannot be adopted, feedback from farmers cannot reach researchers, and overall agricultural development stagnates. Over time, as technologies and social environments change, the methods by which extension communication is carried out have evolved. This article explores the background, prevailing problems, principles, conventional and emerging communication methods, future prospects—especially of ICTs—and concludes with recommendations.

Historically, agricultural extension was often a unidirectional process: researchers develop technologies, extension agents deliver them to farmers, and adoption follows (or not). This linear “transfer of technology” model dominated much of the 20th century extension practice. However, many scholars have argued that this model is insufficient, especially in complex rural settings where local knowledge, farmer participation, social norms, language, resource constraints, and environmental conditions all matter.

In many developing countries (e.g. in Africa, Asia), extension services have been under pressure: budget cuts, insufficient trained staff, low farmer-agent ratio, infrastructural deficits. At the same time, demand for timely information (weather, inputs, markets, pest/disease outbreaks, sustainable methods) has increased. These pressures have prompted greater experimentation with communication models, and the introduction of ICT (Information and Communication Technologies) to supplement or transform traditional methods. Thus, understanding communication methods in agricultural extension is crucial for academics, extension policy makers, NGOs, and farmers alike.

Prevailing Communication Problems in Agriculture

Several problems hinder effective communication in agricultural extension. Some of the main ones are:

- Poor infrastructure & resource constraints : Rural areas often suffer from lack of reliable electricity, roads, internet connectivity. This limits the reach and timeliness of communication.
- Low capacity or training of extension agents and farmers : Many extension workers may not be adequately trained in newer communication technologies or in participatory methods. Farmers may lack literacy, digital skills, or confidence in using ICT tools.
- Mismatch between methods/messages and farmers' needs : Messages may be too technical, poorly timed, not in local languages, or communicated via channels that are not accessible. Sometimes, extension workers are not present or are occupied with other administrative tasks.
- Limited feedback mechanisms : In many cases communication is one-way rather than two-way: extension agents push information, but the voices, problems, and innovations of farmers are not incorporated into the system.
- High cost and access issues of ICTs : Even when ICTs have the potential to greatly increase reach, constraints such as high cost of devices, lack of internet or mobile signal, erratic power, lack of electricity, and lack of software/hardware support limit their use.
- Cultural, social, and literacy barriers : Language differences, cultural norms, low literacy, or resistance to change can all act as impediments. Traditional media (songs, drama, proverbs) may be under-utilized, or local ways of knowledge exchange ignored.
- Overload and irrelevance of information : Farmers may receive information that is not relevant to their agro-ecological conditions, economic situation, or immediate needs. Also, too much information with little prioritization or clarity can confuse rather than help.

These problems jointly reduce adoption rates of innovations, reduce efficiency of extension, and limit the impact of agricultural development efforts.

Principles of Agricultural Extension (Communication-related)

To address these problems, extension communication should rest on certain principles. Key ones include:

- Relevance and appropriateness : Messages must be relevant to the local context: climate, soil, socio-economic conditions, culture, languages, the current capacities of farmers.
- Clarity and simplicity : Avoid unnecessary technical jargon; use clear, understandable language, visuals, demonstrations.
- Two-way communication / participation : Not just transferring information, but gathering feedback, involving farmers in defining needs, co-designing technologies or adaptation. This enhances ownership and increases likelihood of adoption.
- Interactivity and dialogue : Using methods that allow questions, interaction, peer learning and discussion rather than lecture or broadcast only.

- Timeliness : Information needs to reach farmers when they need it (e.g. before planting, during pest outbreaks). Delays reduce usefulness.
- Frequency and consistency : Regular follow-ups, reinforcement, refresher trainings help consolidate knowledge and ensure ongoing support.
- Accessibility : Channels should be accessible physically, economically, socially. That includes geographical accessibility, affordability, literacy accommodations, and cultural sensitivity.
- Use of multiple channels / methods (media mix) : Combining interpersonal contact (visits, demonstrations) with mass media (radio, TV), print, ICTs, etc., to enhance reach, reinforce messages and ensure redundancy.
- Monitoring, evaluation, and feedback : Tracking whether communication efforts are effective; adapting methods based on evidence; ensuring the voices of farmers are heard and reflected.

Communication Methods in Agriculture (Traditional / Conventional)

Below are some of the established communication methods used in agricultural extension.

Method	Description	Strengths	Weaknesses
Interpersonal methods: farm visits, face-to-face meetings, field days, demonstrations, home visits**	Direct interaction between extension agents and farmers, or farmers among themselves.	High trust, can adapt messages to local contexts, allow questions and clarification, strong feedback.	Resource intensive (time, personnel), limited reach, may be costly to maintain, logistical difficulties in remote areas.
Group methods: farmers' groups, cooperatives, group training, field days, farmer-research extension groups**	Messages delivered in group settings.	Efficient to reach many, fosters peer interaction, group learning.	Some farmers may be left out (e.g. women, marginalized groups), group meetings may be infrequent, risk of generalization not fitting specific farms.
Mass media: radio, television, newspapers, posters, brochures, pamphlets**	Dissemination through broadcast or print media.	Large reach; low marginal cost per additional audience; good for simple messages or awareness.	Less ability to tailor messages; often one-way; may not reach remote or illiterate audiences; delayed feedback.
Printed materials: brochures, bulletins, extension guides, posters, fact sheets**	Written/graphic content for reading or viewing.	Can be referred to later; visual; cheap at scale; good for reference.	Requires literacy; may be misinterpreted; distribution challenges; may not be updated.
Visual/audio-visual methods: demonstrations, video shows, slide-projectors**	Use of visual aids, live demonstrations.	Effective for showing processes; better retention; compelling.	Requires equipment; electricity; may be expensive; logistic constraints.

Empirical example: In a study in Kwara State, Nigeria, extension agents used audio methods (farm visits, general meetings, telephone calls) most frequently; written forms were least employed. Factors like number of farmers to reach, nature of message, and characteristics of end-users influenced choice of method.

Emerging Methods of Communication in Agricultural Extension

With changes in technology, environment, and society, several newer methods are supplementing or replacing traditional ones. Some emerging or growing methods:

- Mobile phones / SMS services : Use of SMS or voice calls to send reminders (planting, spraying), market prices, weather forecasts. Easy to scale, relatively low cost.
- Smartphone apps, Internet-based platforms : Advisory apps, crowd-sourced platforms, e-learning, video tutorials. These provide richer content and interactivity.
- Social media : WhatsApp groups, Facebook, Telegram etc for peer sharing, group problem solving, rapid dissemination of alerts (e.g. pest/disease).
- Interactive voice response (IVR), voice messaging systems : For farmers who are illiterate or have low digital skills; they can use voice messages or recorded content.
- Radio and TV with participatory content : Not just broadcasting but allowing farmer interviews, call-ins, discussion forums.
- Satellite / remote sensing / IoT / sensor networks : Use of sensors to monitor soil moisture, weather, pest/disease risk; drone or satellite imagery; these data being communicated to farmers with actionable advisories.
- Participatory sensing and crowd-sourcing : Farmers themselves collect data (pictures, voice, observations) and share with extension systems; sometimes via “human sensors.” For example, experimental systems combining physical and human sensors, voice messages etc in greenhouse farms.
- Delay-tolerant networks (DTNs) and relay networks : In areas with poor connectivity, systems that buffer, relay, or store and forward messages using mobile nodes or intermittent connections to ensure communication flow.
- Precision agriculture communication systems : Use of LoRa, low power wide area networks, other IoT communication technologies to connect sensors, small nodes, and deliver precise advisories. Example: LoRa for Agriculture 4.0 communication opportunities and challenges.
- Blended methods : Combining traditional and modern: e.g. field-days with video projection; SMS plus group meetings; radio shows plus follow-up field visits.

These emerging methods promise higher reach, timeliness, interactivity, and customization.

Future Prospects of ICTs in Agricultural Extension

Information and communication technologies (ICTs) have great potential for transforming agricultural extension. Some prospects:

- Greater adoption of mobile-based advisory services : As mobile penetration increases, more farmers will have access to smartphones. Apps, SMS, voice services can deliver personalized advisories.
- Data-driven extension : Use of big data, remote sensing, weather forecasts, predictive analytics to anticipate pest/disease pressure, climate events etc, and shape recommendations.

- ❖ Artificial Intelligence (AI), machine learning : Chatbots, voice assistants, image recognition (for pests/diseases), decision support systems will support extension agents and farmers.
- ❖ Edge computing / IoT networks : Sensors in fields giving real-time feedback (soil moisture, soil nutrient etc.) and triggering alerts or automated systems (e.g. for irrigation).
- ❖ Use of DTNs and networks suited to low connectivity : For rural or remote areas without stable Internet, systems that can adapt – periodic offline sync, relay nodes, store-and-forward etc.
- ❖ Multimedia, interactive and immersive technologies : Video streaming, augmented reality (AR) / virtual reality (VR) could be used for training farmers in demonstration of complex tasks.
- ❖ Community networks and participatory platforms : Platforms that allow farmers to share local knowledge, innovations, peer learning; integrating social media, messaging groups, voice platforms etc.
- ❖ Policy support, infrastructure improvements : To fully leverage ICTs, need policies that facilitate access (electricity, internet), support subsidies, invest in training, create regulatory frameworks that allow innovation.
- ❖ Localization and linguistic/cultural adaptation : Making content in local languages, adapting to local cultures; using traditional media in combination with ICTs.

Empirical evidence:

A recent systematic review of 49 studies found that ICT-based extension interventions (mobile apps, SMS, video, voice calls) often lead to increased adoption of good agricultural practices, higher yields, improved incomes and better awareness.

Conclusion

Effective communication is indispensable for agricultural extension. While traditional communication methods (interpersonal, group, mass media) remain important, their limitations have become more pronounced in today’s fast-changing, information-rich environment. Emerging methods especially ICT-based offer powerful tools for augmenting reach, timeliness, interactivity, and personalization. However, challenges such as access, cost, infrastructure, literacy, cultural and social mismatches, and ensuring meaningful two-way communication remain. Without dealing with these, ICTs may simply replicate or even exacerbate existing communication inequalities.

Recommendations

Based on the foregoing, the following recommendations are suggested for policy makers, extension agencies, NGOs, and researchers:

- ✓ Capacity building & training : Invest in training extension agents (and farmers) in ICT tools, participatory communication, local languages, cultural sensitivity, etc.
- ✓ Infrastructure development : Improve rural infrastructure: electricity, internet / mobile connectivity; support for low-connectivity solutions.
- ✓ Use of mixed / blended communication approaches : Don’t rely solely on one method; combine interpersonal, group, mass media, ICT etc to maximize effectiveness.
- ✓ Local adaptation of content and methods : Use local languages, traditional media forms (songs, drama, proverbs) in tandem with modern ones; ensure content is relevant to local conditions.

- ✓ Policy support and funding : Governments should make policies that support ICT extension services (subsidies, access, regulation), and allocate sufficient budgets.
- ✓ Strengthen feedback and participatory mechanisms : Build systems for listening to farmers' problems, local innovations, allowing co-design, adjusting messages and methods based on feedback.
- ✓ Monitoring & Evaluation (M&E) : Establish metrics for communication effectiveness (reach, adoption, satisfaction, behavioural change) and monitor them; use learning to refine extension programs.
- ✓ Research & innovation : Ongoing research into which communication methods work best under which conditions; testing new technologies; ensuring inclusivity (for women, marginalized groups).

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DIAZOTROPHIC BACTERIA AS MULTIFUNCTIONAL BIOFERTILIZERS: UNRAVELING THEIR P, K AND ZN SOLUBILISATION ACTIVITIES

Karishma Singh*, Suman Jayakumar Kankanwadi and Vijay Kumar

Department of Microbiology, CCS Haryana Agricultural University, Hisar, Haryana.
*Corresponding Email: sumanjk2708@gmail.com

Abstract
Diazotrophic bacteria, traditionally recognized for their atmospheric nitrogen–fixing capacity, have emerged as potent multifunctional biofertilizers with the ability to solubilize essential mineral nutrients such as phosphorus (P), potassium (K), and zinc (Zn). These processes enhance nutrient bioavailability in the rhizosphere, thereby elevating crop productivity in sustainable agricultural systems. This article reviews the mechanisms underlying their nutrient-mobilization competence, highlights key genera with demonstrable P–K–Zn solubilisation activities, and outlines current challenges to their widespread agronomic adoption. The narrative integrates recent conceptual advances, practical perspectives, and field-level implications to present diazotrophs as holistic nutrient-mobilizing agents capable of reducing chemical fertilizer dependency.

Key words : Diazotrophic, Biofertilizer, Agriculture, Challenges, Solubilization

Introduction

The shift toward eco-efficient agriculture has intensified interest in microbial inoculants capable of improving soil fertility while mitigating environmental degradation. Diazotrophic bacteria—microorganisms capable of reducing atmospheric nitrogen (N_2) into plant-usable ammonia—represent a cornerstone of this paradigm. However, their ecological role extends far beyond nitrogen fixation alone. Increasing evidence shows that many diazotrophs possess additional plant-growth-promoting traits, especially mineral solubilisation via biochemical mechanisms that release otherwise inaccessible nutrients (Jalal *et al.,* 2022). Phosphorus, potassium, and zinc are among the most limiting mineral nutrients in global cropland soils. Their insoluble, inorganic, or tightly adsorbed forms severely restrict plant uptake. Conventional solutions rely on chemical fertilizers, yet these approaches often exhibit poor nutrient-use efficiency and pose risks of eutrophication and soil degradation. In contrast, P–K–Zn-solubilizing diazotrophs enhance nutrient availability through organic acid secretion, proton extrusion, siderophore production, and enzymatic transformations. This multidimensional functionality positions them as sustainable alternatives to synthetic fertilizers. (Renganathan *et al.,* 2025).

Diazotrophy: The Foundational Trait That Enables Multifunctionality

Diazotrophic bacteria derive their significance primarily from their capacity to fix atmospheric nitrogen (N_2) into ammonia (NH_3), which plants cannot obtain directly from the atmosphere. This process is mediated by the nitrogenase enzyme system, a highly energy-intensive but ecologically pivotal mechanism.

Nitrogenase System and Its Biochemical Dynamics

Nitrogenase comprises:

- **Mo–Fe nitrogenase** (molybdenum-dependent),

- **V–Fe nitrogenase** (vanadium-dependent),
- **Fe–Fe nitrogenase** (iron-only variant).

These complexes reduce N_2 via ATP-driven electron transfer. Diazotrophs deploy protective systems—like conformational shielding, high respiratory rates, and slime-layer barriers—to protect nitrogenase from oxidative inhibition. (Jalal *et al.,* 2022).

Ecological Versatility and Rhizosphere Colonization
Diazotrophs thrive in diverse ecological niches because of:

- Their metabolic plasticity,
- Ability to use varied carbon sources,
- Biofilm-producing capabilities,
- Chemotactic movement toward root exudates.

This versatility provides a robust platform for the co-expression of other plant growth–promoting traits, including mineral solubilisation.

Phosphorus Solubilisation: Unlocking a Chemically Locked Nutrient
Phosphate often exists in insoluble complexes with Ca^{2+}, Fe^{3+}, or Al^{3+}, severely restricting its plant availability. Diazotrophic phosphate-solubilizing bacteria (PSB) enhance P bioavailability through chemical and enzymatic strategies (Feng *et al.,* 2024).

Organic Acid–Mediated Solubilisation
Organic acids lower the rhizosphere pH and chelate metal ions, thereby dissolving phosphate complexes. Diazotrophs synthesize:

- **Gluconic acid** (via PQQ-dependent glucose dehydrogenase),
- **Oxalic acid**,
- **Lactic acid**,
- **Malic and citric acids**.

These acids form stable metal-organic complexes, releasing inorganic phosphate ($H_2PO_4^-$) into the soil solution.

Enzymatic Mineralization of Organic Phosphorus
Diazotrophic PSB also secrete:

- **Phosphomonoesterases** (acid and alkaline phosphatases),
- **Phytases** (hydrolyzing phytate-bound P),
- **C–P lyases** (splitting carbon–phosphorus bonds).

These enzymes mineralize organic phosphorus pools that chemical fertilizers cannot access.

Synergistic Role of Diazotrophy in Enhancing P Availability
Nitrogen fixation improves root architecture by stimulating auxin-mediated elongation. A broader root system increases:

- Rhizospheric exudation,
- Microbial colonization,
- P mobilization capacity.

This P–N synergy significantly boosts plant phosphorus nutrition (Lei *et al.,* 2025)

Potassium Solubilisation: Weathering Silicates for Plant Nutrition
Potassium, despite its abundance in soil minerals, remains only partially available to plants. Diazotrophic potassium-solubilizing bacteria (KSB) facilitate the release of K^+ ions from silicate minerals (Pradhan *et al.,* 2025).

Acidolytic Weathering of K-Bearing Minerals

Organic acids secreted by bacteria penetrate the crystal lattice of minerals like mica, biotite, and feldspar. These acids:

- Donate protons (H^+) to substitute K^+ in the mineral matrix,
- Chelate Al^{3+} and Si^{4+},
- Break down silicate structures, freeing potassium.

Role of Extracellular Polysaccharides (EPS)

EPS produced by diazotrophs:

- Form hydrophilic films around mineral particles,
- Create microzones of altered pH,
- Enhance mineral disintegration by retaining moisture and organic acids.

EPS-rich strains often exhibit superior potassium-releasing capabilities.

Diazotrophs Demonstrating K-Solubilisation

Species such as:

- *Azospirillum brasilense*,
- *Herbaspirillum seropedicae*,
- *Burkholderia vietnamiensis*,

have shown prominent K-solubilizing ability under laboratory and field trials (Kulakowski *et al.,* 2025).

Zinc Solubilisation: Addressing Micronutrient Malnutrition

Zinc deficiency is a critical issue in calcareous, alkali soils and presents a global challenge for crop nutrition and human health. Diazotrophic Zn-solubilizing bacteria (ZnSB) mobilize zinc from insoluble salts (Yadav *et al.,* 2023).

Siderophore-Mediated Zn Mobilization

Although siderophores primarily scavenge Fe^{3+}, they enhance zinc mobility by:

- Outcompeting Zn-binding soil ligands,
- Indirectly dissolving ZnO and $Zn_3(PO_4)_2$ complexes,
- Creating microenvironments conducive to metal ion exchange.

Organic Acid Dissolution of Zinc Salts

Acids such as citric and oxalic acid:

- Form soluble complexes with Zn^{2+},
- Dissolve zinc carbonate and zinc phosphate precipitates,
- Promote zinc uptake by maintaining it in ionic form.

Improvement in Crop Zinc Biofortification

Diazotrophic ZnSB help crops accumulate higher Zn in edible tissues, addressing:

- Hidden hunger in humans,
- Poor grain nutritional density,
- Deficiencies in cereal-based diets.

Integrated P–K–Zn Solubilisation: A Multifunctional Nutrient Mobilisation Network

Some diazotrophic strains demonstrate simultaneous P, K, and Zn solubilisation. These multifunctional strains provide a more holistic nutrient mobilization system(Pradhan *et al.,* 2025).

Mechanistic Multiplicity

Such strains exhibit:

- Balanced organic acid secretion,
- Strong chelating compound production,
- Multi-enzyme portfolios,
- Ability to modulate rhizosphere pH dynamically.

Advantages of Multifunctional Diazotrophic Consortia

Consortia of diazotrophs offer:

- Nutrient release synchronization,
- Reduced dependency on chemical fertilizers,
- Better tolerance to abiotic stress,
- Long-term soil fertility enhancement.

Field-Level Outcomes

Applications have shown:

- Increased nutrient-use efficiency
- Higher chlorophyll index,
- Improved grain filling and biomass,
- Enhanced microbial activity and soil restructuring.

Challenges and Future Directions

Despite their potential, several constraints limit mainstream adoption:

Environmental Variability

Microbial survival and function fluctuate with soil pH, moisture, salinity, and temperature. Field performance often deviates from laboratory results.

Competition with Native Microbiota

Introduced diazotrophs must compete with indigenous microorganisms for root niches and carbon sources, which sometimes diminishes their effectiveness.

Limited Shelf Stability of Bioinoculants

Many diazotrophic cultures are sensitive to desiccation, UV radiation, and osmotic stress. Developing robust formulations (encapsulation, carrier-based systems) remains a challenge.

Strain-Specific Performance

Not all strains exhibit strong P–K–Zn solubilisation concurrently. Identifying elite, multifunctional strains requires extensive screening and genomic validation.

Regulatory and Commercialization Barriers

Biofertilizer standardization, quality assurance, and registration protocols vary widely between regions, slowing commercialization (Aslam *et al.,* 2024).

Conclusion

Diazotrophic bacteria, long celebrated for biological nitrogen fixation, now hold promise as comprehensive nutrient-mobilizing agents through their capacity to solubilize phosphorus, potassium, and zinc. Their biochemical versatility, ecologically benign nature, and compatibility with sustainable agricultural practices make them indispensable for the future of soil fertility management. Although challenges in field efficacy, formulation stability, and commercialization persist, ongoing advances in microbial ecology, genomics, and inoculant technology are rapidly expanding their agronomic potential. Harnessing multifunctional diazotrophic strains represents a transformative step toward reducing the global reliance on chemical fertilizers while building resilient, nutrient-efficient cropping systems.

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EMPOWERING INDIA'S FARMERS: AN EVOLVING STRATEGY FOR INCOME SECURITY AND AGRICULTURAL TRANSFORMATION

Hanumanthappa, R[1*], Ashwitha A S Gowda[2], Bhavith Jain B[3], Ajjayya M[4], Vidya Kumar Jagalur[5]

[1&2] Ph.D. Scholars, Department of Agricultural Economics,
University of Agricultural Sciences, Bengaluru, Karnataka – 560065
[3&4] M.Sc. Scholars, Department of Agricultural Economics,
University of Agricultural Sciences, Bengaluru, Karnataka – 560065
[5] Ph.D. Scholars, Department of Agricultural Extension,
University of Agricultural Sciences, Bengaluru, Karnataka – 560065
*Corresponding Email: hanumar1998@gmail.com

Abstract

Indian agriculture has evolved from a focus on food self-sufficiency to a broader strategy that prioritises farmers' income security, sustainability and agri-entrepreneurship. Farmer Producer Organisations (FPOs) have become central to this transformation by facilitating crop diversification, technology adoption, value addition and stronger market linkages. Agriculture has sustained an annual growth rate of about 5 per cent, contributing nearly 18 per cent to Gross Value Added (GVA) and employing 46 per cent of the workforce. India is now self-sufficient in staples like rice and wheat and nearly self-sufficient in pulses, with production rising from 17.15 million tonnes in 2014-15 to 25.41 million tonnes in 2017-18. In 2024-25, food grain output is estimated at 353.96 million tonnes, oilseeds at 426.09 lakh tonnes, while horticulture production has overtaken food grains at 367.72 million tonnes. The government's strategy for income security includes raising productivity through high-yielding and climate-resilient varieties, reducing cultivation costs via concessional credit, mechanisation and input subsidies and ensuring remunerative returns through Minimum Support Price (MSP) procurement. Simultaneously, investments in post-harvest infrastructure under the Agriculture Infrastructure Fund and promotion of high-value and biofortified crops are strengthening farm incomes. A notable innovation is the Digital Agriculture Mission, which leverages AgriStack-based farmer IDs, land records and digital crop surveys to deliver transparent and targeted services, including credit, subsidies and MSP procurement. Despite persistent challenges such as fragmented holdings, infrastructure gaps and limited digital literacy, the convergence of institutional reforms, financial tools and digital infrastructure is reshaping Indian agriculture. The shift positions farmers as agri-entrepreneurs, ensuring food and nutritional security, higher incomes and resilience to climate and market risks.

Keywords: Farmer Producer Organisations, Income security, Digital agriculture, Crop diversification, Agricultural transformation

Introduction

In recent years Farmer Producer Organisations (FPOs) have come to play a pivotal role in India's agricultural revolution. By encouraging crop diversification, integrating modern technologies and adding value after harvest, they are helping shift from merely producing staple crops to ensuring farmers can earn sustainable livelihoods. While self-sufficiency in staples like rice, wheat and pulses remains a priority, the government's agricultural policies are now explicitly geared towards treating farmers as **agri-entrepreneurs**, with income security at the heart of these reforms.

Agriculture in the Indian Economy: Trends & Achievements

- Agriculture continues to employ nearly 46 per cent of India's workforce, even though it contributes about 18 per cent to the Gross Value Added (GVA). Over the past decade, the sector has grown at an average rate of around 5 per cent annually.
- India has achieved self-sufficiency in major food grains such as rice and wheat. In the mid-2010s, pulses were a weak point India imported heavily, and domestic production lagged. Strategic interventions in productivity, expansion of cultivable area, and guaranteed procurement have reversed that trend. For example, pulses production rose from 17.15 million tonnes in 2014-15 to 25.41 million tonnes in 2017-18.
- Latest official estimates for 2024-25 show record food grain production of about 353.96 million tonnes, up by 6.5 per cent over the previous year. Oilseed production rose by roughly 7.4 per cent, reaching around 426.09 lakh tonnes. Meanwhile, horticulture has shown robust growth and has now outpaced food crops, with an approximate horticulture output of 367.72 million tonnes.
- Land use stats: in 2022-23, the net sown area was about 14.07 lakh hectares, with a gross cropped area of ~2193 lakh hectares. Cropping intensity stood at ~155.9 per cent. Irrigation coverage is about 56.37 per cent, with ~793.12 lakh hectares under irrigation.

These figures underscore not just growth in quantity but also improvements in productivity, cropping patterns and investment in inputs and infrastructure.

Multi-Pronged Strategy for Farmers' Income Security

To move beyond food self-sufficiency and towards ensuring income security, the government has adopted a strategy composed of several interlocking components:

- **Boosting Production & Productivity:** The development and rapid deployment of high-yielding, hybrid, climate-resilient and biofortified seed varieties (through ICAR, state universities) have raised yields and stabilized production even under environmental stresses. Anonymous, 2023
- **Reducing Cost of Cultivation:** Measures include subsidised inputs (fertilisers, seeds), concessional short-term credit via the Kisan Credit Card scheme with interest subvention and prompt repayment incentives, mechanisation via subsidised tools and establishment of farm machinery banks, etc.
- **Ensuring Remunerative Prices:** Minimum Support Price (MSP) policies for multiple crops (both Kharif and Rabi, including jute, copra etc.) have been reinforced; procurement operations have been scaled up to prevent distress sales and support farmer income.
- **Post-Harvest Value Addition & Infrastructure:** The Agriculture Infrastructure Fund under the Atmanirbhar Bharat initiative provides interest subvention for loans related to cold storage, pack houses, grading, sorting and other post-harvest facilities. This helps reduce losses after harvest, improves quality, expands shelf life and enables better prices.
- **Crop Diversification & High-Value / Differentiated Varieties:** There is active push toward higher-value crops (horticulture, oilseeds, etc.), exotic or differentiated varieties, value added products, organic farming, certified seed production, etc., so that farmers can access premium segments of the market.

- **Risk Mitigation:** Schemes for crop insurance, climate-smart agricultural practices, resilient varieties (to drought, pests, diseases), soil health cards, etc., are helping reduce exposure to climatic, price and input-cost risks.
- **Technology, Innovation & Digital Infrastructure:** Increasing use of ICT, AI, satellite imagery, mobile apps, advisory services, decision support systems, etc., to support farmers through the crop cycle—from sowing to marketing.

Institutional & Policy Enablers

- **ICAR and Research Bodies** have played a central role. Between 2014-2024, India's National Agricultural Research System (ICAR + State/Central Agricultural Universities) developed about 2,900 improved crop varieties / hybrids, spanning cereals, oilseeds, pulses, fibre, forage, etc. Out of these, ~2,661 are tolerant to one or more abiotic or biotic stresses. Anonymous, 2023
  In the same period, 152 biofortified crop varieties (rice, wheat, maize, millets, pulses, oilseeds, etc.) have been released, strengthening both yield and nutritional security. Anonymous, 2023
- **Financial Instruments** like the Kisan Credit Card (KCC), interest subvention schemes, subsidy regimes for fertilisers and inputs and support for agricultural mechanisation are helping lower the financial burden on farmers.
- **Minimum Support Price (MSP) & Procurement** programmes to guarantee floor price and large-scale procurement systems to secure farmers' income.
- **Cluster-based Farming & FPOs**: To overcome issues of small, fragmented land holdings and low bargaining power, the government has promoted Farmer Producer Organisations. FPOs enable economies of scale, better market linkages, collective value addition and greater negotiation power. States are supporting FPOs with ease of licensing (for input supply), regulatory support (e.g. FSSAI, GST) and facilitation in value-added roles.

Digital Transformation & Public Infrastructure

One of the cornerstones of the evolving agricultural policy is the Digital Agriculture Mission, with the AgriStack or Digital Public Infrastructure (DPI) being central to this transformation. Key components include:

- **Farmer Registry / Farmer ID**: Every farmer who owns land is to be issued a unique digital identity ("Farmer ID"), linked with demographic data, mobile number, land plot numbers, share in plots, etc. This helps in eliminating repeated verification steps when availing loans, subsidies, inputs, MSP procurement etc (Anonymous, 2024).
- **Georeferenced Land Plot Registry**: Mapping of farm plots with GPS / GIS so that land records, ownership, cropping etc. are tied to digital spatial data.
- **Crop Sown Registry / Digital Crop Survey**: Using on-ground surveys (often via mobile apps) linked to georeferenced plots soon after sowing, with photographic evidence and digital uploads of crop information. This helps in accurate estimation of acreage per crop, helps in planning, forecasting and policymaking (Anonymous, 2024).
- **Complementary Services**: The DPI supports more efficient crop loans (KCC), MSP procurement, input subsidies, crop insurance, etc., by allowing verification via Farmer ID rather than manual checks. It also enables more precise advisory services (weather, pests, diseases), because the system has plot-level, crop-wise, farmer-wise data. Anonymous, 2025

- Recent numbers: As of mid-2025, more than 6.5 crore (65 million) Farmer IDs have been created under the Digital Agriculture Mission (Anonymous, 2025). Some states are making good progress; e.g. Gujarat became the first state to generate Farmer IDs for 25 per cent of its target (Anonymous, 2023).

Outcomes & Challenges

Positive Outcomes:

- Higher incomes through better price realisation and reduced post-harvest loss thanks to investment in cold storage, grading, pack houses.
- Reduction in cultivation costs due to mechanisation and better input supply.
- Better risk management through insurance, resilient seed varieties.
- Improved transparency and efficiency in delivery of subsidies, credit and scheme benefits via digitised verification systems.
- Enhanced nutritional security via biofortified varieties.

Challenges still to be addressed:

- Fragmented holdings continue to limit investments and economies of scale, especially for small and marginal farmers. FPOs help, but scaling them sustainably remains a task.
- Adoption of new technologies, differentiated/high-value crops, or biofortified seeds can be slow (due to seed availability, habit, risk aversion).
- Infrastructure gaps persist in many regions (irrigation, storage, transport, cold chain).
- Implementation of digital systems must ensure data privacy, transparency, ease of use, and reach even in regions with poor connectivity or low digital literacy.
- Ensuring that MSMEs/FPOs can access markets, licensing, regulatory compliance (GST, FSSAI etc) without disproportionate burden.

Conclusion

India's agricultural policy has been evolving from the twin goals of food security and self-sufficiency in staple crops to a more nuanced framework where income security, nutritional security, and sustainable, technology-enabled agriculture are front and centre. The combination of improved crop varieties, financial and input support, modern infrastructure, FPOs, and digital public infrastructure (including Farmer IDs, georeferenced land and crop surveys) is gradually transforming the landscape. While significant progress has been made, especially in the past few years, the way forward involves ensuring that these reforms reach every farmer, including those in remote or marginal lands; that the benefits are equitable; and that systems are resilient to climate risks and market fluctuations.

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THE PATH OF SUSTAINABLE FARMING UNDER CLIMATE UNCERTAINTY

K. N. Tiwari[1]* and Yogendra Kumar[2]

[1] Former Director, International Plant Nutrition Institute, India Program, Kanpur
[2] Marketing Director, IFFCO, Saket, New Delhi
*Corresponding Author: kashinathtiwari730@gmail.com

Abstract

Agriculture today stands at a critical crossroads, where sustaining productivity and profitability must align with environmental resilience in the face of increasing climate uncertainty. This paper explores the multidimensional path toward sustainable farming systems capable of adapting to erratic rainfall, rising temperatures, and frequent extreme weather events. It examines the interlinkages between soil health, water management, crop diversification, and the integration of climate-smart technologies that enhance both ecological and economic sustainability. Emphasis is placed on the role of resource-efficient innovations such as precision agriculture, nano-fertilizers, integrated nutrient management, and renewable energy use in reducing carbon footprints. The study also highlights policy frameworks, institutional supports, and community-based adaptation strategies that empower farmers to manage risk and build resilience. By synthesizing scientific evidence and practical approaches, the paper outlines a holistic roadmap for transitioning to sustainable farming practices that ensure food, nutrition, and livelihood security under changing climatic conditions.

Introduction

Agriculture has always been the cornerstone of human civilization and the backbone of global food security. It not only provides food, fruits, vegetables, milk, and other essential commodities but also supports the livelihoods of nearly 2.5 billion people across the world. In developing nations like India, agriculture contributes significantly to the national economy and rural employment, serving as a source of sustenance and socio-economic stability for millions of small and marginal farmers. As the global population is projected to rise to around 9.7 billion by 2050 (FAO, 2022), the demand for food, feed, fiber, and fuel will continue to increase substantially. This unprecedented growth places immense pressure on the agricultural sector to produce more with fewer resources and within shrinking ecological limits.

However, the agricultural landscape today is undergoing a period of heightened uncertainty due to the escalating impacts of **climate change**. Rising global temperatures, shifting rainfall patterns, frequent droughts, floods, cyclones, and unseasonal weather events are disrupting traditional farming systems. These climatic extremes not only reduce crop productivity and soil fertility but also increase the vulnerability of livestock, fisheries, and other allied sectors. As a result, farming communities face growing economic stress, declining farm incomes, and greater risks of food insecurity. Moreover, unsustainable agricultural practices—such as overuse of chemical fertilizers and pesticides, excessive groundwater extraction, and monocropping—have aggravated soil degradation, biodiversity loss, and greenhouse gas (GHG) emissions, further weakening the resilience of agro-ecosystems.

The dual challenge of **feeding a growing population** while **adapting to climate uncertainty** calls for a transformative shift towards sustainable and climate-resilient farming systems. This transformation must focus on optimizing the use of natural resources, promoting integrated farming systems, enhancing soil and water conservation, and diversifying crops to reduce climate-related risks. The adoption of innovative technologies—such as precision agriculture, digital weather forecasting, stress-tolerant crop varieties, and renewable energy solutions—offers promising pathways for increasing productivity sustainably.

Sustainable farming, in this context, is not merely about maintaining yields but about building resilience—resilience of soils, water systems, crops, and rural communities. It integrates ecological balance, economic viability, and social equity to ensure that agricultural development today does not compromise the needs of future generations. Collaborative action among farmers, researchers, policymakers, and extension agencies is therefore vital to achieving this vision. In light of these pressing challenges, this paper explores **"The Path of Sustainable Farming under Climate Uncertainty"-** examining the interlinkages between climate change and agriculture, identifying key adaptation and mitigation strategies, and suggesting policy and technological pathways to secure the future of food systems. The focus lies on developing climate-smart, resource-efficient, and inclusive agricultural practices that ensure food and nutrition security while safeguarding the environment.

Factors Influencing Climate Uncertainty in India

Climate uncertainty in India arises from a complex interplay of natural, anthropogenic, and socio-economic factors. These elements interact dynamically, shaping the intensity, frequency, and distribution of climatic events such as droughts, floods, and heatwaves. Understanding these influencing factors is essential to designing effective adaptation and mitigation strategies for sustainable agricultural development.

Greenhouse Gas Emissions and Global Warming: One of the most critical drivers of climate uncertainty is the rapid rise in greenhouse gas (GHG) concentrations in the atmosphere, mainly due to industrialization, fossil fuel combustion, and agricultural emissions. India, being the third-largest emitter globally, faces a dual challenge—curbing emissions while sustaining economic growth. Methane (CH_4) from livestock and rice paddies, nitrous oxide (N_2O) from fertilizers, and carbon dioxide (CO_2) from energy and transport sectors contribute significantly to warming trends that alter monsoon behaviour and temperature extremes.

Monsoon Variability and Ocean-Atmosphere Interactions: The Indian monsoon system is highly sensitive to oceanic phenomena such as:

- **El Niño–Southern Oscillation (ENSO)** and **La Niña**, which alter sea surface temperatures in the Pacific Ocean, affecting rainfall patterns across the subcontinent.
- **Indian Ocean Dipole (IOD)**, influencing the southwest monsoon strength and distribution.
- **Arabian Sea and Bay of Bengal warming**, which intensifies cyclonic activities and changes precipitation dynamics.

These variations create unpredictability in the timing, duration, and intensity of monsoon rains, leading to both droughts and excessive rainfall events.

Land Use and Land Cover Changes: Rapid urbanization, deforestation, and agricultural expansion have led to significant land use and land cover (LULC) transformations, disrupting local climatic feedback mechanisms. The replacement of forests with croplands and built-up areas alters surface albedo, evapotranspiration rates, and carbon sequestration capacity. Such changes contribute to regional climate anomalies, including increased local temperatures (urban heat islands) and altered rainfall regimes.

Aerosol Concentrations and Air Pollution: India experiences one of the highest aerosols load globally, arising from biomass burning, vehicular emissions, industrial pollution, and dust storms. Aerosols influence cloud formation and solar radiation balance, leading to "solar dimming"-a reduction in sunlight reaching the Earth's surface. This can suppress convection and delay monsoon onset while intensifying localized precipitation events, adding another layer of unpredictability to India's climate system.

Water Resource Stress and Hydrological Imbalance: Altered precipitation patterns and glacial retreat in the Himalayas contribute to the decline of river flows and groundwater levels. Seasonal variability in rainfall affects recharge rates and leads to regional water stress. Uncertain hydrological cycles influence irrigation availability, reservoir storage, and agricultural planning, exacerbating vulnerabilities to drought and floods.

Agricultural and Industrial Practices: Unsustainable farming practices—such as excessive use of fertilizers, stubble burning, and groundwater overexploitation—intensify local climate impacts. Simultaneously, industrial emissions and energy consumption contribute to regional warming and pollution. The feedback loops between land degradation, air quality, and climate variability amplify uncertainties at both micro and macro levels..

Socio-Economic and Institutional Factors: Socio-economic disparities, inadequate infrastructure, and limited access to climate-resilient technologies hinder adaptive capacity. Fragmented policy implementation, insufficient climate data, and lack of integrated planning further limit effective response mechanisms. Institutional coordination between agriculture, water, and environment sectors remains weak, amplifying the impacts of climatic variability.

Natural Variability and Geographical Factors

India's diverse geography—from the Himalayas to coastal plains—creates wide regional differences in climate response. The Himalayan cryosphere plays a crucial role in regulating monsoon patterns, while coastal zones face increasing cyclonic activity due to sea surface warming. Natural variability in solar radiation and volcanic activity also intermittently influences the subcontinental climate system.

Apparently. climate uncertainty in India is the outcome of interlinked environmental, socio-economic, and technological processes. Anthropogenic emissions, oceanic interactions, deforestation, aerosol loading, and water stress collectively reshape weather patterns and intensify climate risks. Effective mitigation demands a multi-sectoral and science-driven approach, integrating climate modelling, sustainable resource management, and policy coordination to enhance resilience against future climatic unpredictability.

Climate-Impacts on Indian Farming

Indian agriculture, the backbone of the nation's economy, is increasingly under stress due to the impacts of climate variability and change. With more than 50% of India's workforce and nearly 18% of the national GDP linked to agriculture, the sector's vulnerability to climatic shifts poses a critical challenge for food security, rural livelihoods, and sustainable development. Climate-affected farming in India is now characterized by rising production risks, resource degradation, and changing agro-ecological dynamics.

Changing Cropping Patterns and Seasons: Climate change has altered cropping calendars, growing seasons, and the spatial distribution of crops across different agro-climatic zones. Delayed monsoons and early withdrawal periods disrupt sowing times, forcing farmers to shift from water-intensive crops like rice and sugarcane to drought-tolerant crops such as millets, pulses, and oilseeds. In some regions, double-cropping systems are becoming unviable due to declining soil moisture and increasing temperature extremes.

Example: The traditionally rice-dominant eastern states are witnessing a gradual shift toward maize and millets, while northern states like Punjab and Haryana face declining wheat yields due to shortened growing windows and high night-time temperatures.

Declining Crop Productivity: Rising temperatures, erratic rainfall, and frequent extreme weather events have led to measurable reductions in crop yields. The Indian Council of Agricultural Research (ICAR) estimates that, without adaptive measures, wheat yields may decline by 6–10% for every 1°C increase in temperature. Similarly, rice yields could fall by 4–6% due to heat stress and water scarcity. These productivity losses directly threaten national food security and export potential.

Soil Health Deterioration: Intense rainfall, prolonged dry spells, and the overuse of chemical fertilizers under uncertain climatic conditions are degrading India's soil resources. Changing temperature and rainfall patterns are expanding drylands and desert areas, particularly in Rajasthan, Bundelkhand, and central India. India loses about 21 tons of soil per hectare and the Indo-Gangetic plains lose around 16 tons of soil per hectare annually. The country loses 5.3 billion tonnes of soil annually through erosion, reducing its arable land potential. Declining organic carbon, micronutrient deficiencies, and salinity build-up in irrigated zones further reduce soil fertility and resilience. The combined effect of climate and unsustainable land use practices has weakened the natural regenerative capacity of Indian soils. Heavy rains and floods cause topsoil erosion, washing away valuable organic matter and nutrients. Drought conditions, especially in Rajasthan and Gujarat, accelerate wind erosion and soil crusting. Declining soil organic carbon and nutrient losses reduce fertility, microbial activity, and water-holding capacity.

Unsustainable land-use practices, deforestation, overgrazing, and faulty irrigation, accelerate the degradation process. The conversion of fertile land into wasteland reduces biodiversity and carbon sequestration capacity, weakening the ecological resilience of entire regions. Climate-induced soil and water degradation poses a long-term challenge to agricultural sustainability. Climate-induced soil and water degradation poses a long-term challenge to agricultural sustainability. As a result, farmers need more fertilizers and irrigation to maintain productivity—creating a cycle of dependency and degradation.

Rainfall Variability: Rainfall uncertainty-such as delayed onset of monsoon, erratic distribution, or premature withdrawal—poses a serious challenge for rainfed and irrigated agriculture alike. Drought conditions cause severe water stress, reducing soil moisture and affecting seed germination and crop establishment. On the other hand, excessive or untimely rainfall leads to waterlogging, root damage, and nutrient loss. Irregular rainfall patterns also disrupt irrigation schedules and increase the demand for groundwater extraction, putting further stress on already depleted aquifers. Farmers in monsoon-dependent regions like South Asia are particularly vulnerable to such inconsistencies.

Apparently, rainfall variability is one of the most visible indicators of climate uncertainty. In India and other monsoon-dependent regions, the seasonal pattern of precipitation is becoming increasingly erratic and unreliable**.** The onset of the monsoon is often delayed, and its retreat occurs earlier, disrupting sowing schedules and shortening the growing period. “Flood-to-drought” situations are becoming frequent- a few days of intense downpour followed by prolonged dry spells. Heavy rains lead to flash floods, soil erosion, and loss of farm infrastructure, while prolonged dry periods cause moisture stress and poor germination. Poor drainage systems lead to waterlogging and salinity, rendering land unproductive. Continuous nutrient leaching and chemical imbalances reduce soil fertility and yields. These irregularities not only reduce crop yields but also disturb irrigation management, groundwater recharge, and nutrient balance in the soil. For farmers, this means greater uncertainty in planning and higher dependence on weather forecasting tools and contingency crop planning.

Water Scarcity and Irrigation Stress: Water availability is emerging as a defining constraint for Indian farming under a changing climate. Uneven rainfall distribution, declining groundwater reserves, and melting Himalayan glaciers are leading to water stress in major agricultural regions. The over-extraction of groundwater in north western India, combined with erratic rainfall in peninsular regions, threatens both irrigated and rainfed agriculture. Future projections indicate that nearly 60% of India’s district**s** could face water scarcity by 2050 unless adaptive irrigation practices are adopted. Water scarcity is emerging as a critical bottleneck for sustainable agriculture. Irregular rainfall results in poor recharge of ponds, tanks, and aquifers. Excessive groundwater extraction for irrigation has caused alarming declines in water tables, especially in Punjab, Haryana, and Gujarat. Melting glaciers in the Himalayas initially cause floods but eventually reduce long-term river flow. This dual problem of scarcity and degradation highlights the urgency of water conservation, micro-irrigation, and rainwater harvesting initiatives.

Increased Incidence of Pests, Diseases, and Weeds: Climate variability influences pest and pathogen dynamics, leading to new infestations and extended breeding cycles. Warmer and humid conditions foster pest outbreaks like *Helicoverpa, Fall Armyworm*, and *whitefly*, affecting cotton, maize, and vegetable crops. Shifts in weed flora-such as the spread of *Parthenium hysterophorus*-add further production challenges. Crop diseases like wheat rust, rice blast, and late blight are becoming more frequent and severe under variable weather conditions. Apparently, warmer climates promote the proliferation of invasive pests such as the fall armyworm, which has devastated maize crops across the country.

Changes in temperature and humidity patterns also influence the geographical distribution and life cycles of pests and pathogens. The growing use of pesticides increases costs, affects biodiversity, and undermines environmental health. These outbreaks increase dependence on chemical pesticides, raising production costs and environmental hazards. Integrated Pest Management (IPM) and biological control measures thus become vital in reducing both vulnerability and ecological footprint.

Impact on Livestock and Allied Sectors: Livestock productivity, a critical component of rural livelihoods, is also affected by climate stress. Livestock face increased risks from vector-borne diseases like bluetongue and Rift Valley fever, which are spreading into new areas. Heat stress reduces milk yield, fertility, and feed conversion efficiency in cattle and buffalo. Water scarcity and degraded pasturelands affect fodder availability. Similarly, fisheries and aquaculture are suffering from warming waters, ocean acidification, and altered breeding cycles, particularly in coastal states

Economic Losses and Farm Distress: Climate-related shocks-such as floods, droughts, and cyclones-lead to recurrent economic instability for farmers. Crop failures and yield fluctuations increase indebtedness and distress migration. According to the Economic Survey (2023), climate shocks account for an average annual farm income loss of 15–18%, with small and marginal farmers being the most affected due to limited access to technology, insurance, and institutional credit.

Regional Disparities in Climate Impact: The severity of climate effects on farming varies widely across India:

- **North India:** Heat stress and groundwater depletion affecting wheat-paddy systems.
- **East India:** Floods and prolonged waterlogging reducing rice productivity.
- **Central India:** Drought-prone conditions impacting pulses and oilseeds.
- **South India:** Declining rainfall and rising temperatures affecting horticultural and plantation crops.
- **Western India:** Desertification and salinity intrusion threatening crop viability.

Socio-Economic and Gender Dimensions: Climate-affected farming also has significant social implications. Women farmers, who make up nearly 30% of the agricultural workforce, face increased labour burdens, limited access to credit, and reduced decision-making power. Youth are migrating from villages due to uncertain agricultural incomes, leading to aging rural populations and labour shortages in key farming regions.

Pathways for Resilience: To mitigate these challenges, Indian agriculture must transition toward climate-resilient farming systems through:

- Diversification of crops and income sources.
- Adoption of water-saving technologies and precision irrigation.
- Integration of digital weather advisories and early warning systems.
- Promotion of soil health management and conservation agriculture.
- Strengthening crop insurance and risk-transfer mechanisms.

These measures can collectively enhance the adaptive capacity of Indian farmers, ensuring sustainable productivity even under climatic uncertainties.

Mitigation and Adaptation Strategies

To make agriculture climate-resilient and sustainable, a combination of technological, ecological, and institutional measures is essential as detailed below:

A. Climate-Smart Practices

- Adoption of climate-resilient crop varieties (heat-, drought-, and flood-tolerant).
- Promotion of soil and water conservation measures such as contour bunding, terracing, and mulching.
- Integrated farming systems combining crops, livestock, horticulture, and fisheries to diversify income sources.

- Utilization of digital technologies—mobile apps, sensors, and weather forecasting tools for timely decision-making.
- Strengthening of crop insurance, credit facilities, and farmer training programs.
- Encouragement of organic and low-carbon farming to enhance soil health.

B. Crop Management under Climate Uncertainty

- Selection of drought- and flood-tolerant crops such as millets, pigeon pea, and chickpea.
- Utilization of traditional crop diversity and indigenous knowledge for risk management.
- Adoption of crop rotation and mixed farming to improve soil structure and resilience.
- Shift from water-intensive crops (rice, wheat) toward pulses, oilseeds, and millets.
- Use of micro-irrigation systems (drip and sprinkler) and rainwater harvesting to improve water use efficiency.
- Improvement of soil health through biofertilizers, nano-fertilizers, and compost.
- Implementation of Integrated Pest Management (IPM) and use of AI-based advisories for timely interventions.
- Integration of precision farming and weather-based crop insurance to minimize losses.

C. Fertilizer Management in Climate Uncertainty

- Implementation of the 4R Nutrient Stewardship Principle: *Right Source, Right Rate, Right Time, and Right Place.*
- Soil test-based and crop stage-specific nutrient application.
- Use of enhanced-efficiency fertilizers such as coated or slow-release types and innovative products like IFFCO Nano Urea Plus, Nano DAP, Nano Zinc and Nano copper.
- Flexible nutrient management according to seasonal weather conditions.
- Promotion of conservation agriculture to increase soil organic carbon.
- Integration of agroforestry for shade, wind protection, and carbon sequestration.
- Use of compost and farmyard manure to enhance soil structure and fertility.

D. Water Management Strategies

- Construction of farm ponds, check dams, and percolation tanks for rainwater harvesting.
- Expansion of micro-irrigation systems to reduce water loss.
- Enhancement of groundwater recharge through infiltration pits and vegetative bunds.
- Adoption of zero tillage, mulching, and residue management to retain soil moisture.
- Deployment of smart irrigation systems integrated with weather forecasts and soil moisture sensors.

E. Technology and Equipment in Climate Adaptation

Modern technology offers new opportunities to anticipate, mitigate, and manage climatic risks.

- Mobile Applications and Digital Platforms such as *IFFCO Kisan*, *Meghdoot*, and *Kisan Suvidha* provide location-specific weather forecasts, crop advisories, and early warnings.
- Remote Sensing and Drones help monitor soil moisture, crop health, and post-disaster damage assessments.
- Artificial Intelligence (AI) and Machine Learning predict extreme weather, pest outbreaks, and disease risks, enabling proactive response.

The combined use of these tools enhances resilience, reduces losses, and optimizes productivity, ensuring that farming remains viable even under uncertain climatic conditions.

Benefits of Climate-Resilient Agriculture

Stable Yield: One of the most direct and visible advantages of climate-resilient agriculture is its ability to maintain stable yields during periods of climatic stress such as droughts, floods, or heatwaves The shift toward Climate-resilient agriculture offers a wide array of agronomic, ecological, economic, and social benefits, making it essential for achieving food and livelihood security under changing climate conditions as described below:

- The use of drought and heat-tolerant crop varieties, along with timely weather-based advisories, enables farmers to cope with unpredictable rainfall and temperature fluctuations.
- Diversified farming systems combining crops, livestock, horticulture, and fisheries—reduce the risk of total crop failure, ensuring a consistent flow of food and income even in adverse conditions.
- Improved soil structure and organic matter through conservation tillage and residue management enhance water retention and nutrient availability, helping crops withstand dry spells.

Thus, CRA transforms vulnerability into resilience by building adaptive capacity at the field level, ensuring food production stability for farming communities.

Conservation of Soil and Water Resources: Climate-resilient farming emphasizes efficient resource use and ecological balance, which are key to sustaining agricultural productivity over time. The benefits of Climate-resilient farming are :

- Soil conservation practices such as contour bunding, cover cropping, mulching, and agroforestry prevent erosion and restore soil fertility.
- Rainwater harvesting, micro-irrigation, and watershed development improve water use efficiency, recharge groundwater, and reduce dependency on erratic rainfall.
- Organic amendments (compost, green manures, and biofertilizers) enhance soil microbial activity and carbon sequestration, improving soil health and resilience to drought.
- Reduced tillage and crop residue management help retain moisture, lower soil temperature, and protect beneficial organisms.

These integrated measures not only sustain productivity but also support ecosystem regeneration, ensuring that land and water resources remain viable for future generations.

Reduced Costs and Lower Greenhouse Gas Emissions: Climate-resilient agriculture promotes resource-efficient and low-carbon farming systems, aligning agricultural growth with environmental protection. The following strategies may be adopted to achieve the goal of reduced costs and lower Greenhouse Gas Emissions:

- The use of precision technologies-such as site-specific nutrient management, sensor-based irrigation, and drone-based monitoring-optimizes input use, reducing waste and costs.
- Integrated Nutrient Management (INM) and 4R fertilizer practices (Right Source, Right Rate, Right Time, Right Place) minimize nutrient losses, lower input costs, and cut nitrous oxide emissions.
- Adoption of renewable energy solutions like solar pumps, biogas units, and energy-efficient equipment reduces dependence on fossil fuels.
- Practices such as zero tillage, crop residue recycling, and agroforestry contribute to carbon sequestration, helping to mitigate global warming.

Overall, CRA provides a win–win approach—reducing environmental impacts while improving profitability through smart resource utilization.

Stable Income and Diversified Livelihoods: A cornerstone of climate-resilient agriculture is its emphasis on livelihood diversification, which safeguards farmers from market and climatic uncertainties as mentioned below:

- By integrating multiple enterprises such as crop cultivation, dairy, poultry, fishery, beekeeping, and agroforestry farmers can access various income streams throughout the year.
- Diversification also encourages value addition and agro-processing, allowing smallholders to capture better market prices.
- Stable productivity and reduced input costs lead to steady farm incomes, lowering the risk of debt and distress migration.
- Community-based approaches, such as Farmer Producer Organizations (FPOs) and cooperatives, strengthen collective bargaining and access to markets and finance.

These strategies help transform rural farming from a vulnerable occupation into a resilient livelihood system that can withstand environmental and economic shocks.

Empowered Farmers through Digital and Institutional Support: Modern climate-resilient agriculture integrates digital innovation, data-driven decision-making, and institutional capacity-building to empower farmers as highlighted below:

- Mobile-based advisory platforms (e.g., *Meghdoot*, *IFFCO Kisan*, *Kisan Suvidha*) deliver localized weather forecasts, pest alerts, and agronomic recommendations directly to farmers.
- Artificial Intelligence (AI) and remote sensing technologies enable real-time monitoring of soil moisture, crop health, and climatic risks, allowing farmers to make informed choices.
- Farmer field schools and training programs enhance knowledge about sustainable practices, enabling communities to adopt climate-smart technologies effectively.
- Insurance schemes and risk-transfer mechanisms protect farmers from catastrophic losses due to weather extremes.

The empowerment of farmers through such digital and institutional interventions fosters a sense of self-reliance, confidence, and innovation**,** ensuring long-term adaptation and resilience.

Contribution to National and Global Goals: Beyond individual and community-level benefits, climate-resilient agriculture supports the broader agenda of sustainable development and climate action as given below:

- It aligns with the UN Sustainable Development Goals (SDGs)-particularly SDG 2 (*Zero Hunger*), SDG 13 (*Climate Action*), and SDG 15 (*Life on Land*).
- By reducing emissions, enhancing carbon sinks, and improving ecosystem health, CRA contributes to the Paris Agreement targets on climate mitigation.
- Strengthened agricultural resilience ensures national food security, rural employment, and environmental sustainability—key pillars of inclusive growth.

The Road Ahead

Strengthening Research and Innovation

- Promote interdisciplinary research integrating climate science, agronomy, soil health, and socio-economics to develop adaptive and location-specific solutions.

- Invest in the development and dissemination of climate-resilient crop varieties that can withstand heat, drought, and salinity stresses.
- Encourage innovation in nano-fertilizers, bio-stimulants, and smart irrigation systems to improve resource-use efficiency and reduce environmental degradation.

Enhancing Farmer Capacity and Knowledge Systems

- Establish farmer field schools, digital learning platforms, and community-based extension models to disseminate knowledge on sustainable practices.
- Strengthen collaboration between research institutions, extension agencies, and local governance bodies to ensure technology transfer and farmer participation.
- Promote indigenous and traditional knowledge systems as complementary tools for climate adaptation.

Policy and Institutional Reforms

- Formulate climate-smart agricultural policies that incentivize sustainable practices such as crop diversification, organic farming, and integrated pest and nutrient management.
- Ensure financial inclusion through climate risk insurance, accessible credit, and subsidies for eco-friendly technologies.
- Establish institutional frameworks for integrated water resource management and sustainable land use planning.

Promoting Digital and Data-Driven Agriculture

- Expand the use of remote sensing, GIS, and AI-based forecasting tools for real-time monitoring of weather, pests, and soil conditions.
- Develop decision-support systems that enable farmers to make informed choices about cropping patterns, irrigation scheduling, and nutrient management.
- Encourage public–private partnerships for the deployment of digital infrastructure in rural areas.

Strengthening Community Resilience and Resource Management

- Promote collective farming, farmer-producer organizations (FPOs), and cooperative models to enhance access to inputs, markets, and risk-sharing mechanisms
- Support watershed management, agroforestry, and soil conservation programs to restore degraded ecosystems and enhance ecosystem services.
- Encourage gender-inclusive and youth-focused initiatives to ensure equitable participation in sustainable agriculture transitions.

Global and National Collaboration

- Facilitate international cooperation for sharing climate data, research outcomes, and best practices in sustainable agriculture.
- Align national agricultural development strategies with global frameworks, such as the UN Sustainable Development Goals (SDGs) and the Paris Climate Agreement, to ensure coherence and accountability.

Conclusion

The transition toward sustainable farming under climate uncertainty requires coordinated efforts across research, policy, technology, and community engagement. Building resilience is a long-term commitment that must integrate innovation, inclusion, and institutional support at every level.

These recommendations provide a roadmap for policymakers, researchers, and practitioners to collectively advance a climate-resilient and sustainable agricultural future. In this way, CRA is not only a pathway for adapting to climate uncertainty but also a powerful instrument for achieving long-term global sustainability.

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ENOKI MUSHROOM (*Flammulina velutipes*): FROM FOREST FLOORS TO GLOBAL SUPERFOOD

Sneha Shikha*, Prachi Singh, Priya Bhargava and Shraddha Bhaskar Sawant

Department of Plant Pathology, Bihar Agricultural University, Sabour
*Corresponding Email: shikhamaanya@gmail.com

Enoki mushroom (*Flammulina velutipes*) is an important edible and medicinal fungus cultivated globally. Among the world of edible fungi, *F. velutipes* stands out as both a culinary delicacy and a medicinal treasure. Its mild taste, crunchy texture, and impressive health benefits have made it a staple in Asian cuisine and an increasingly popular ingredient in global markets. Today, it ranks as the fourth most widely cultivated mushroom, with major production concentrated in China, Japan, Korea, and Vietnam. This article reviews the taxonomy, distribution, morphological features, nutritional and medicinal attributes, and cultivation technology of Enoki mushroom.

Flammulina velutipes belongs to the **Physalacriaceae** family of the **Basidiomycota** division and shares its genus with more than fifteen related species. Of these, *F. velutipes* and *F. rossica* are the most widespread and well-documented. The mushroom's global popularity is also reflected in its many cultural names—*Enokitake* in Japan, *Jin Zhen Gu* in China, *Paengibeoseot* in Korea, *Heand* in India, *zimska panjevica* in Serbia, and *fetuitui* in Cameroon. In English, it is commonly called golden needle mushroom, winter mushroom, velvet stem, or shank mushroom, names that describe its delicate form and seasonal fruiting habit.

Taxonomic Rank	**Classification**
Kingdom	Fungi
Division	Basidiomycota
Class	Agaricomycetes
Order	Agaricales
Family	Physalacriaceae
Genus	*Flammulina*
Species	*Flammulina velutipes* (Curtis) Singer

One of the most remarkable features of Enoki is its ability to thrive in winter. Unlike most fungi that prefer warm and humid environments, it has evolved adaptations that allow it to fruit in freezing temperatures. Its cell membranes contain highly unsaturated phospholipids that remain flexible in the cold, while protective compounds such as glycerol, arabitol, and trehalose serve as natural antifreeze agents. These adaptations explain why Enoki, also known as the "winter mushroom," is found fruiting in harsh conditions when other fungi disappear.

Natural habitat

In the wild, *F. velutipes* is a wood-decaying fungus that colonizes the trunks and stumps of deciduous trees and occasionally parasitizes weakened living trees. It fruits in dense clusters across temperate regions of North America, Europe, and Asia, especially during winter. For centuries, foraging for Enoki was a seasonal tradition, particularly in Asia and Europe.

Cultivation History and Global Rise

The history of Enoki cultivation stretches back to the Tang Dynasty in China (around 800 AD), where early growing methods were recorded. In Japan, systematic cultivation began in the 1920s on sawdust and rice bran substrates, with major technological advances during the 1960s that transformed production. By the 1980s, Japan's output had exceeded 62,000 tons, ranking Enoki second only to Shiitake. By the 1990s, China surpassed Japan with over 200,000 tons of production annually. Today, China dominates the mushroom industry, producing nearly 40 million tons of mushrooms in total, while Japan remains a significant contributor with more than 127,000 tons of Enoki reported in 2022. Globally, mushroom cultivation is projected to exceed 20 million tons annually by 2026, fueling a multibillion-dollar industry.

Morphological Characteristics of Wild and Cultivated *Flammulina velutipes*

The wild form of *F. velutipes* has an orange to yellow-brown convex-shaped cap, initially measuring 1.5–6.5 cm in diameter with an in-rolled margin. As it matures, the cap becomes flat with a central hump and eventually develops a flaring margin. The cap surface is shiny, moist, and sticky when fresh. The gills are broad, adnexed to sinuate, and subdistant, showing a yellowish-white coloration. Supporting the cap is a flexible cylindrical stipe measuring 2–7 cm × 0.3–1.0 cm. This stalk lacks a ring and appears yellowish-white, gradually darkening to brown at the base during maturity. The spores are smooth, ellipsoid in shape, and measure 6.5–9.0 µm × 2.5–4.0 µm.

The cultivated form of *F. velutipes* shows a distinct appearance compared to its wild counterpart. Commercially farmed Enoki mushrooms are recognized by their less sticky caps, which are significantly smaller in size, with diameters ranging from 1–3 cm. The cap is borne on finely clustered, pubescent stipes measuring 1.5–7 cm × 0.2–0.7 cm. Both cap and stipe are pure white in colour due to growth in dark conditions and exposure to high carbon dioxide levels during cultivation. These environmental factors result in thin, elongated, and soft stalks, which are highly desirable for culinary applications.

Nutritional and Medicinal Importance

Enoki mushrooms are valued as much for their health benefits as for their culinary uses. Rich in dietary fibre, essential vitamins, and minerals, they are also a source of bioactive polysaccharides with wide-ranging medicinal properties. The mushroom is consumed not only due to its nutritional value but also its medicinal properties; 76 secondary metabolites have been isolated, characterised, and reported to show a range of health benefits. Traditional communities in Jammu and Kashmir consume *heand* as an immune-boosting tonic, while Himalayan healers historically used it in managing diabetes. Modern scientific studies support these practices, identifying anticancer, antimicrobial, antioxidant, cholesterol-lowering, and immunomodulatory compounds within Enoki. These findings establish it not only as a versatile food ingredient but also as a functional food with immense therapeutic promise.

Cultivation Technology

The Enoki mushroom available in supermarkets is primarily cultivated under controlled conditions to produce the characteristic long, thin, white fruiting bodies. Traditionally, *F. velutipes* was cultivated on wood logs, but since the quality of fruit bodies obtained from logs was inferior, modern cultivation now relies on sawdust-based substrates. These substrates are often mixed with supplements such as rice bran or wheat bran to improve nutrient availability.

Substrate Preparation – Sawdust (from hardwoods such as Cryptomeria or aged pine) is supplemented with 5% rice bran or wheat bran. In India, sawdust of hardwoods with wheat or rice bran is commonly used. The mixture is soaked for 16–18 hours to ensure proper hydration.

Bag or Bottle Filling – About 2 kg of substrate is filled into polypropylene bags or 800–1000 ml bottles, plugged with cotton stoppers, and sterilized at 121 °C for 1.5–2 hours.

Inoculation and Incubation – Once cooled, the substrate is inoculated with grain or sawdust spawn. Incubation is carried out at 20–25 °C in darkness for 20–25 days, until the mycelium fully colonizes the substrate. At this stage, the compact surface inoculum is scraped off to promote even fruiting.

Fruiting Induction – Environmental changes trigger primordia formation: temperature is lowered to 10–14 °C, relative humidity maintained at 80–85%, and the bags kept in dark conditions. Primordia appear within 10–14 days.

Fruiting and Growth Control – For high-quality mushrooms, the temperature is further reduced to 3–5 °C with air circulation at 3–5 m/s. Plastic collars are often fitted to the neck of bottles to ensure vertical, elongated growth.

Harvesting – Mushrooms are harvested when they reach 13–14 cm in height, usually 50–60 days after inoculation. A first flush yields 100–140 g per bottle, with a second flush producing 60–80 g.

Post-Harvest Handling – The delicate mushrooms are vacuum-packed to preserve texture and shipped to markets worldwide.

Challenges and Future Prospects

Despite the increasing popularity of Enoki cultivation, several challenges persist — including climate sensitivity, and post-harvest perishability. Research into improved substrate formulations, low-cost cultivation techniques, and strain improvement for tropical adaptation is ongoing. Expanding Enoki production in India could enhance rural livelihoods and diversify the mushroom industry.

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FOOD SAFETY IN THE BANANA AND PLANTAIN VALUE CHAIN

Oluwatoyin Zaka, David Ahmed Adamu*, Chinwendu Vivian Oheari,
Jumoke Taofeequat Ayilara

Research Outreach Department, Nigerian Stored Products Research Institute
*Corresponding Email: adamuad@nspri.gov.ng

Abstract

Bananas and plantains are vital to food security and economic stability in sub-Saharan Africa, yet their safety and quality are often compromised throughout the value chain from cultivation to consumption. This review examines key food safety challenges and proposes strategies to enhance the safety and sustainability of banana and plantain production and trade. Pathogens such as *Colletotrichum musae*, *Fusarium oxysporum*, and *Aspergillus niger* proliferate under moist postharvest conditions, leading to spoilage and potential mycotoxin contamination. By improving postharvest management, enforcing regulations, and promoting behavioral change, stakeholders can build a more resilient and trustworthy food system. Safe banana and plantain products will not only protect consumers but also open new opportunities for regional and international trade. Implementing regular food safety training, promoting the use of solar-powered cold rooms, strengthening policy enforcement, encouraging public campaigns, and processing plantain into chips, flour, and puree under hygienic conditions can reduce losses and enhance food safety compliance.

Keywords: Postharvest, Banana, Plantain, Safety, Spoilage

Introduction

Banana and plantain are not just staple foods; they are vital sources of income and nutrition for millions of households in sub-Saharan Africa. However, the safety and quality of these fruits are often compromised along the value chain from cultivation and harvesting to transportation, ripening, and marketing. Understanding and managing food safety hazards in this chain are essential for consumer health, market competitiveness, and sustainable livelihoods. The banana and plantain value chain is complex and highly perishable. Postharvest handling, poor infrastructure, and limited awareness of safety standards contribute to the contamination of fruits by microbes, chemical residues, and spoilage agents. According to Olayemi and Adegbola (2022), over 30% of harvested banana and plantain in West Africa are lost or downgraded due to unsafe handling and improper storage practices.

The major practices that continually affect banana and plantain were excessive pesticide use, coupled with inadequate knowledge and enforcement, results in residue accumulation exceeding Codex standards. The use of calcium carbide and other unsafe chemicals for fruit ripening alters the taste, texture, and nutritional quality, posing health hazards. Exposure to dust, flies, and open-air contaminants in markets increases microbial load. Lack of cold chain systems accelerates deterioration. Income levels, education, access to technology, and market distance influence the quality and safety of bananas and plantains. Traders often prioritize short-term profit over safe handling due to inadequate facilities or awareness. Ensuring food safety in the banana and plantain value chain is not just a health issue it is an economic and developmental necessity.


Key Food Safety Challenges in the Value Chain

1. Microbial Contamination: Pathogens such as Colletotrichum musae, Fusarium oxysporum, and Aspergillus niger thrive in moist postharvest conditions, leading to spoilage and potential mycotoxin contamination (Adebayo & Yusuf, 2023).
2. Chemical Residues: Farmers often use pesticides beyond recommended limits. Inadequate knowledge and lack of enforcement result in residue accumulation exceeding Codex standards (FAO, 2022).
3. Artificial Ripening Agents: The use of calcium carbide and other unsafe chemicals for fruit ripening alters the taste, texture, and nutritional quality, posing health hazards (Ehiowemwenguan & Emoghene, 2021).
4. Poor Market and Storage Conditions: Exposure to dust, flies, and open-air contaminants in markets increases microbial load. Lack of cold chain systems accelerates deterioration (Owolabi & Oke, 2022).

Socioeconomic and Behavioral Factors

The quality and safety of banana and plantain are strongly influenced by socioeconomic determinants such as income levels, education, access to technology, and market distance. Traders often prioritize short-term profit over safe handling due to inadequate facilities or awareness. Alamu and Adesokan (2023) observed that market women commonly store overripe plantains in unsanitary environments, unaware of the microbial risks involved.

Conclusion

Ensuring food safety in the banana and plantain value chain is not just a health issue it is an economic and developmental necessity. By improving postharvest management, enforcing regulations, and promoting behavioral change, stakeholders can build a more resilient and trustworthy food system. Safe banana and plantain products will not only protect consumers but also open new opportunities for regional and international trade.

Recommendations for Safer Value Chains

1. Training and Awareness: Implement regular food safety training for farmers, traders, and market vendors on hygienic handling, pesticide application, and safe ripening methods.

2. Infrastructure and Technology: Promote the use of solar-powered cold rooms, hermetic storage, and edible coating technologies to extend shelf life safely.
3. Policy Enforcement: Strengthen the monitoring capacity of agencies like NAFDAC and SON to regulate chemical use and market sanitation.
4. Consumer Education: Encourage public campaigns on identifying safely ripened fruits and the dangers of chemically ripened produce.
5. Value Addition: Processing plantain into chips, flour, and puree under hygienic conditions can reduce losses and enhance food safety compliance.

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BIOPESTICIDES AND ITS ROLE IN TRANSFORMING INDIAN AGRICULTURE

Aman Kumar[1] and Radheshyam Ramkrishna Dhole[2*]

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Sasaram, Rohtas – 821305
[2]Assistant Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Sasaram, Rohtas – 821305
*****Corrosponding Email: akamankumar957040@gmail.com

Abstract

Biopesticides have emerged as a sustainable alternative to chemical pesticides in modern agriculture. In India, where agriculture supports nearly half of the population, the excessive use of synthetic pesticides has resulted in environmental contamination, pest resistance, soil degradation and health hazards. Biopesticides—derived from natural organisms such as bacteria, fungi, viruses, and botanical extracts—offer eco-friendly pest control while maintaining crop productivity. This article discusses the background of biopesticides in India, their key features, methods of application, and their contribution to transforming Indian agriculture. It also highlights the challenges, current progress and future strategies needed to promote widespread adoption of biopesticides for ensuring sustainable food production and environmental safety.

Background

The Green Revolution in the 1960s significantly boosted agricultural productivity in India through the adoption of high-yielding varieties, synthetic fertilizers and chemical pesticides. Although this helped India achieve food security, the excessive reliance on agrochemicals has led to long-term consequences. Continuous applications of chemical pesticides have caused pest resurgence, pesticide resistance and loss of biodiversity. Residues on food and contamination of soil and water pose major health risks for both farmers and consumers.

India is among the world's top pesticide users, yet per hectare productivity remains comparatively low due to soil fatigue and pest adaptation. The need for a cleaner, safer and more sustainable farming system has paved the way for biopesticides. The Government of India, agricultural universities, and research institutions have been promoting biopesticides through organic farming missions, Integrated Pest Management (IPM) programs and subsidies to reduce dependence on synthetic pesticides.

Key Features of Biopesticides

Biopesticides possess unique features that differentiate them from chemical pesticides and make them particularly suitable for Indian farming conditions.

a. **Eco-friendly and safe :** Biopesticides do not leave toxic residues in soil, water or crops. They are safe for humans, animals, pollinators and beneficial organisms.
b. **Target-specific activity :** Unlike broad-spectrum synthetic chemicals, biopesticides act mainly on specific pests, minimizing unintended impacts on ecosystems.

c. **Biodegradability :** Biopesticides degrade naturally and do not cause long-term environmental pollution.
d. **Resistance management :** Since many biopesticides act through multiple mechanisms, the risk of pests developing resistance is much lower compared to chemical pesticides.
e. **Improved soil and crop health :** Many microbial biopesticides simultaneously promote plant growth and suppress soil-borne diseases, leading to healthier crops.
f. **Lower entry barriers for rural entrepreneurship :** Biopesticide production at small and medium scale encourages rural enterprises, self-employment and low-cost pest control solutions.

Methods and Applications

Biopesticides are applied using different techniques depending on crop type, pest species and formulation. Their major categories include:

1. Microbial Biopesticides

These include beneficial bacteria, fungi, viruses and protozoa used to suppress pests and diseases.

Microorganism	Target Pest/Disease	Examples
Bacteria	Lepidopteran larvae & soil pathogens	*Bacillus thuringiensis* (*Bt*), *B. subtilis*
Fungi	Insect pests and nematodes	*Trichoderma viride, Beauveria bassiana*
Viruses	Lepidopteran insects	NPV (Nuclear Polyhedrosis Virus)

Microbial biopesticides can be applied by seed treatment, soil incorporation, foliar sprays, root dip treatment, and drip irrigation.

2. Botanical Biopesticides

Plant-based extracts and essential oils act as repellents, antifeedants, and growth inhibitors. Neem (*Azadirachta indica*) is the most widely used botanical biopesticide in India and globally. It is effective against over 400 pests and is commonly applied as neem oil, neem cake, or azadirachtin formulations.

3. Biochemical Biopesticides

These include pheromones, kairomones and plant growth regulators that interfere with pest mating and development. Pheromone traps are increasingly used in cotton, sugarcane and horticultural crops to monitor and suppress pest populations.

4. Plant-Incorporated Protectants (PIPs)

These involve modifying plant DNA to express pesticidal properties, such as Bt cotton, which contains Bacillus thuringiensis genes that kill bollworms.

Role in Transforming Indian Agriculture

Biopesticides are contributing significantly to sustainable agricultural transformation in India in the following ways:

a. **Reducing dependence on chemical pesticides :** Farmers using biopesticides report significant reductions in synthetic pesticide use while maintaining yield, lowering production costs, and reducing health risks.

b. **Promoting organic and residue-free farming :** With growing demand for organic fruits, vegetables and grains in domestic and international markets, biopesticides enable farmers to meet residue-free standards.
c. **Restoring soil fertility and biodiversity :** Continuous use of biopesticides fosters microbial diversity in soil, increases nutrient availability and improves soil structure.
d. **Enhancing resilience to climate change :** Biopesticides improve crop tolerance to abiotic stresses and make agricultural ecosystems more resilient to pest outbreaks intensified by climate change.
e. **Boosting farmer income and rural entrepreneurship :** Small-scale manufacturing units for Trichoderma, Pseudomonas fluorescens and neem-based products have generated new opportunities for local employment.
f. **Supporting Integrated Pest Management (IPM) adoption :** Biopesticides complement mechanical, cultural and biological practices to create long-term sustainable pest management systems.

Conclusion

Biopesticides hold immense potential in ensuring environmentally friendly and economically viable agriculture. Their adoption can reduce the harmful effects associated with chemical pesticides while safeguarding ecosystem services and human health. India has already taken substantial steps through policymaking, research and extension programs to promote biopesticides; however, challenges such as limited awareness, inconsistent quality, short shelf-life and lack of subsidies compared to synthetic pesticides still hinder large-scale adoption.

Future Strategy

To mainstream biopesticides in Indian agriculture, the following strategies are recommended:

1. Strengthening research and innovation : Development of broad-spectrum, climate-resilient and longer-shelf-life formulations should be prioritized through public-private partnerships.
2. Quality regulation and certification Standardized production protocols, quality monitoring and licensing of manufacturers can ensure efficacy and farmer confidence.
3. Greater financial incentives Subsidies, tax benefits and low-interest loans can promote both production and adoption of biopesticides at a national scale.
4. Training and awareness programs Demonstrations, farmer-to-farmer learning and digital extension platforms should be used to disseminate knowledge on field-level application.
5. Integration in government schemes Mandating biopesticide use under IPM, PM-Kisan, ATMA, and National Mission on Sustainable Agriculture (NMSA) can encourage rapid adoption.
6. Support for start-ups and rural production units Incubation centres and skill development programs can promote local entrepreneurship, employment and availability of high-quality biopesticides.

Biopesticides are not merely an alternative to chemical pesticides but a foundation for a sustainable and regenerative agricultural ecosystem. Their integration into mainstream Indian agriculture can contribute significantly to food security, environmental safety and farmers' prosperity.

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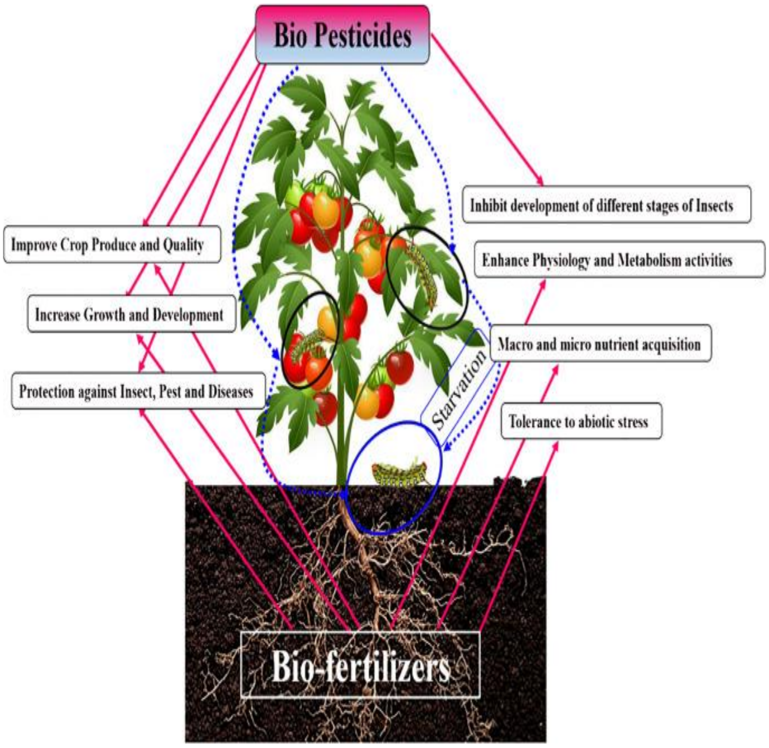

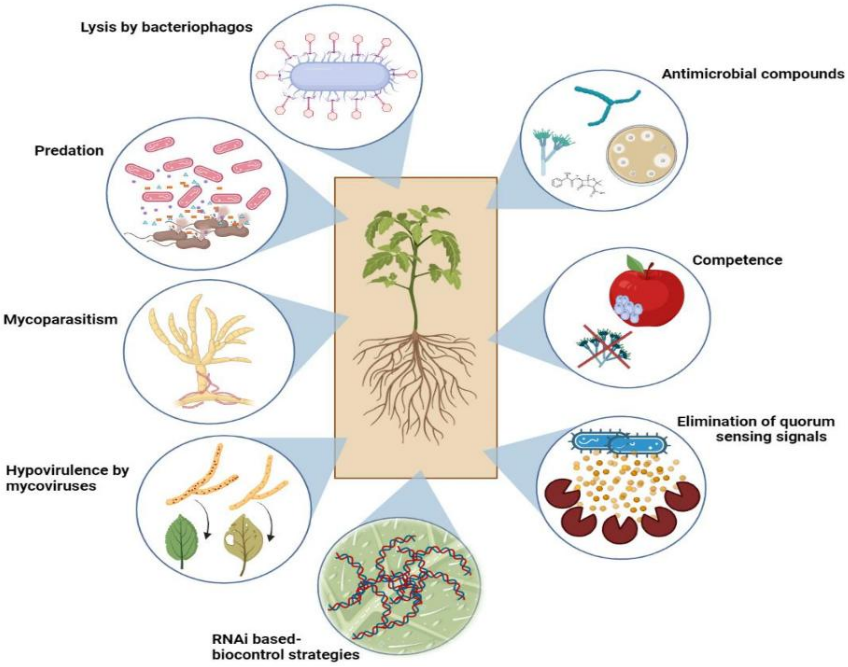

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FATS ON YOUR PLATE: WHICH ONES TO EAT AND WHICH TO AVOID

Poonam Bakhetia

Department of Food and Nutrition, College of Community Science,
Punjab Agricultural University, Ludhiana-141004
Corresponding e-mail: poonambakhetia@pau.edu

Introduction

Fats are one of the three major macronutrients in our diet, along with carbohydrates and proteins. For a long time, fat was considered harmful, associated only with obesity, heart disease, and "unhealthy food." However, modern nutrition science has shown that not all fats are equal. Some types of fat are essential for good health, while others can be harmful if consumed in excess. The key lies in understanding which fats are healthy, which are unhealthy, and how much fat should form part of our daily diet.

Role of Fats in the Human Body

Fats are more than just a source of calories:

- They provide 9 kcal per gram, making them the most energy-dense nutrient.
- They are important for absorption of fat-soluble vitamins (A, D, E, K).
- They form a structural part of cell membranes and support hormone synthesis.
- Essential fatty acids like linoleic acid (omega-6) and alpha-linolenic acid (omega-3) cannot be synthesized by the body and must be obtained from food.
- Fats also contribute to satiety, taste, and texture of foods.

Thus, fats are necessary—but the type and quantity matter.

Recommended Dietary Allowance (RDA) of Fats

According to the Indian Council of Medical Research – National Institute of Nutrition (ICMR-NIN, 2020):

Table 1. Recommended Intake of Fats (ICMR-NIN, 2020)

Nutrient / Type of Fat	Recommended Intake (Adults)	Remarks
Total Fat	20–30% of daily energy	Balance is key
Visible Fat (cooking oil, ghee)	25–40 g/day	Depends on activity level
Saturated Fat (SFA)	<10% of daily energy	Found in ghee, butter, coconut oil
Trans Fat (TFA)	<1% of daily energy	Ideally zero; avoid vanaspati, fried snacks
Omega-3 Fatty Acids (ALA)	1–2 g/day	From flaxseed, walnuts, mustard oil
Omega-6:Omega-3 Ratio	5–10:1	Indian diets often >20:1 (imbalanced)

Types of Fats in Foods

1. Healthy Fats

These promote heart health, reduce inflammation, and support brain function.

- **Monounsaturated Fatty Acids (MUFA):**
  - ✓ Found in olive oil, groundnut oil, mustard oil, nuts, and avocados.
  - ✓ Benefits: Improve cholesterol levels, lower risk of heart disease, provide antioxidants like vitamin E.

- **Polyunsaturated Fatty Acids (PUFA):**
  - ✓ Found in sunflower oil, safflower oil, soybean oil, flaxseed, walnuts, fatty fish.
  - ✓ Includes omega-3 and omega-6 fatty acids.
  - ✓ Benefits: Essential for brain development, reduce blood triglycerides, protect against cardiovascular disease.

- **Omega-3 Fatty Acids (ALA, EPA, DHA):**
  - ✓ Sources: Flaxseed, chia seeds, walnuts, mustard oil (ALA); fish like salmon, sardine, mackerel (EPA, DHA).
  - ✓ Benefits: Anti-inflammatory, improve memory, reduce risk of stroke and diabetes complications.

✓ **RDA for ALA (adult):** 1–2 g/day.

2. Unhealthy Fats

These raise the risk of obesity, diabetes, hypertension, and heart disease.

- **Saturated Fatty Acids (SFA):**
  - ✓ Sources: Ghee, butter, coconut oil, palm oil, full-fat dairy, fatty meats.
  - ✓ Excess intake raises LDL cholesterol ("bad cholesterol").
  - ✓ Should be limited to <10% of total daily energy (ICMR, WHO).

- **Trans Fatty Acids (TFA):**
  - ✓ Found in vanaspati, margarine, bakery shortening, deep-fried fast foods, packaged snacks.
  - ✓ Formed during hydrogenation of oils and repeated reheating of oils.
  - ✓ Even small amounts increase risk of heart attack, diabetes, and obesity.
  - ✓ WHO recommends elimination of industrial trans fats; intake should be <1% of total energy.

Quick Comparison: Healthy vs. Unhealthy Fats

Table 2. Healthy vs. Unhealthy Fats: Sources and Effects

Category	Food Sources (Examples)	Effect on Health
Healthy Fats	Olive oil, mustard oil, groundnut oil, soybean oil, flaxseed, walnuts, fatty fish, almonds	Improve cholesterol, reduce heart disease risk, anti-inflammatory, essential for brain and vision
Unhealthy Fats	Butter, ghee (excess), coconut oil (excess), palm oil, vanaspati, margarine, bakery shortening, repeated fried foods	Increase LDL cholesterol, raise heart disease and diabetes risk, promote obesity

Fat Consumption Patterns in Indian Context:

- Average visible fat intake in urban India: 35–45 g/day (higher in affluent groups).
- Rural India: 20–25 g/day, sometimes below recommended levels.

- Commonly used oils in India: Mustard, groundnut, sunflower, soybean, palm, and more recently olive and rice bran oils.
- Traditional diets were naturally rich in omega-3 from mustard oil and green leafy vegetables. Modern diets, however, have shifted towards refined oils, fried foods, and packaged snacks, increasing the share of omega-6 and trans fats.

Simple Guide to Choosing Fats (Traffic Light Approach)

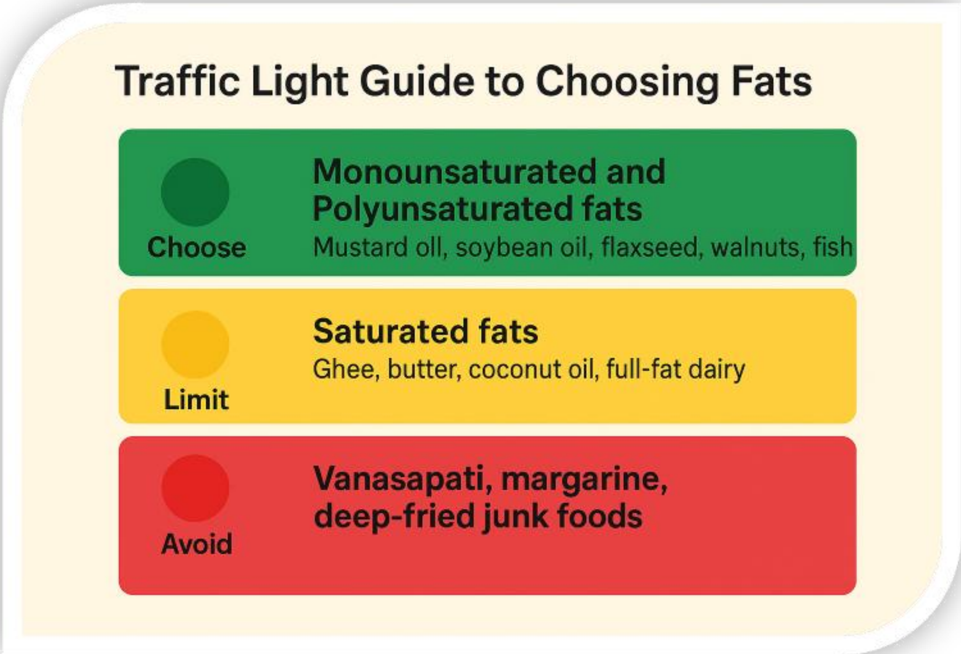

Figure 1

Green Zone (Healthy Fats – Eat Regularly in Moderation):
- Mustard oil, groundnut oil, soybean oil, rice bran oil
- Flaxseed, walnuts, almonds, fatty fish

Yellow Zone (Limit Intake):
- Ghee, butter, coconut oil, full-fat dairy

Red Zone (Avoid as Much as Possible):
- Vanaspati, margarine, bakery shortening
- Deep fried junk foods, packaged snacks

Practical Tips for Choosing Healthy Fats
1. **Use a combination of oils** – No single oil is perfect. Rotate or blend oils (e.g., mustard + sunflower, groundnut + rice bran).
2. **Prefer MUFA and PUFA-rich oils** – Mustard, groundnut, soybean, sesame, rice bran.
3. **Limit saturated fats** – Use ghee, butter, coconut oil sparingly.
4. **Completely avoid trans fats** – minimize bakery shortening, vanaspati, deep-fried junk foods.

5. **Eat natural omega-3 sources** – Flaxseed powder (1–2 tsp/day), walnuts, green leafy vegetables, fatty fish (2 servings/week).
6. **Practice moderation in frying** – Avoid reusing cooking oil, especially for deep frying.
7. **Check food labels** – Look for “0 trans fat” and “low saturated fat” claims.

Key Facts and Figures

- **Energy value of fat:** 9 kcal/g (more than double carbs/protein).
- **Recommended visible fat intake:** 25–40 g/day for adults.
- **Saturated fats:** limit to <10% of daily energy.
- **Trans fats:** <1% of daily energy (ideally zero).
- **Omega-6:Omega-3 ratio:** desirable 5–10:1 (current Indian diet often have 20:1 or higher).
- **ICMR RDA for Omega-3 (ALA):** 1–2 g/day.

Conclusion

Fats are not enemies; they are essential nutrients when chosen wisely. The real danger lies not in fat itself, but in wrong type of fat and excess consumption. Indians today face a “double burden” of under nutrition in some groups and lifestyle diseases like obesity and heart disease in others. By understanding the difference between healthy fats (MUFA, PUFA, omega-3) and unhealthy fats (excess SFA, trans fats), families can make smarter choices in the kitchen.
For healthy longevity and disease prevention, the golden rule is:

“Moderation in quantity, variety in oils, and zero tolerance for trans fats.”

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GREEN PLASTICS FOR FOOD PACKAGING: PROGRESS, CHALLENGES, AND FUTURE DIRECTIONS

Aman Pal[1*], Akash Deep Shukla[2], Sweta Rai[2], Mohd Abbas[1] and Aditi Sharma[1]

[1]Department of Post-Harvest Process and Food Engineering, College of Technology, GBPUAT, Pantnagar, Uttarakhand, India

[2]Department of Food Science and Technology, College of Agriculture, GBPUAT, Pantnagar, Uttarakhand, India

*Corresponding Email: palaman7017@gmail.com

Abstract

The modern lifestyle has been greatly impacted by the widespread use of plastics, on the other hand, it have contributed to one of the most pressing environmental issues. The accumulation of plastic waste that cannot be degraded has caused environmental and human health problems. The food packaging sector is now upgrading from petroleum-based materials to green plastics made from biodegradable and renewable sources. The significant biopolymers are polylactic acid (PLA), polyhydroxyalkanoates (PHAs), thermoplastic starch (TPS), and cellulose or protein-based films. Besides, this article discuss about the impact of active or smart packaging technologies, bio-composites, and nanocomposites in augmenting the functionality and extending the shelf life of food. Moreover, the assessments of economics and the environment point out that despite bioplastics originating from renewable materials with a lower carbon footprint, they still carry disadvantages such as being expensive to produce, requiring careful moisture control, and the absence of sufficient composting infrastructure. Green plastics are necessary invention for sustainable food packaging.

Keywords: Green Plastics, Bioplastics, biodegradable packaging, thermoplastic starch, PLA, green composites, food packaging.

Introduction

In 2018, global plastic production almost reached 360 million tons, with packaging being the major contributor at about 30% of total consumption. Plastics as one of the most important synthetic materials ever invented (Rahardiyan *et al*., 2023). Though very versatile and useful, the plastic industry still heavily relies on fossil fuels that eventually cause big pollution problems. The marine environment receives about 10 million tons of plastic waste every year, leading to an unbalance in nature, contamination with microplastics, and even health risks for humans (Rahardiyan *et al*., 2023). The problem of plastic waste in the oceans globally is aggravated by the use of synthetic polymers and the lack of sufficient recycling plants. Plastics that demonstrate one or more eco-friendly characteristics, like biodegradability, renewability, or the use of eco-friendly processes in their production, are known as "green plastics". One of the major achievements in the history of the concept, although the idea is still considered a new one, is the production of cellulose-based plastics, such as celluloid and cellophane, in the 19th century. Nevertheless, the situation of the industry changed drastically in the post-World War II period with the complete replacement of the petroleum-based polymers, which had better mechanical properties and lower costs (Kuruppalil, 2011).

Green plastics, or renewable and biodegradable materials, have come to the market amid these apprehensions, presenting a choice that is sustainable over the non-renewable plastics. "Green" is termed for the plastics that come from renewable resources, are non-polluting and can either be composted or biodegraded (Kuruppalil, 2011). Different bioplastic varieties such as thermoplastic starch (TPS), polylactic acid (PLA), polyhydroxybutyrate (PHB), and polycaprolactone (PCL) are capable of reducing the carbon footprint substantially and giving a greater good to the ecosystem (Din *et al*., 2020; Maurizzi *et al*., 2022). The food packaging sector shows promising opportunities that drives the sustainable change. Nowadays consumers prefer type of packaging material that not just keeps the safety and quality of the food but also reduces environmental load. The increasing demand for sustainability worldwide, the EU's proposed circular economy plans and ban on single-use plastic. This is possible with the invention and acceptance of bio-based and biodegradable packaging materials (Markevičiūtė & Varžinskas, 2022).

The Environmental Imperative for Green Packaging

The ecological footprint of traditional plastics has been highly negative. These polymers such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are hardly degraded and thus can live in the environment for very long up to hundreds of years (Ncube *et al*., 2020). This lead to a continuous piling up of these materials in the landfills which are now overflowing, and the microplastics have invaded and got widespread in the terrestrial and in the aquatic environments (Din *et al*., 2020). Moreover, incinerating plastic waste is a usual mode of disposal that not only emits toxic and greenhouse gases but also contributes to global warming (Rahardiyan *et al*., 2023). Globally, just more than 9% of plastic waste gets recycled, concludes that the recycling actions taken are still very low. Packaging for food is considered a major hurdle due to problems related to contamination and the low economic viability of recovery (Salwa *et al*., 2019). So, the switch to biodegradable packaging made from renewable biological resources is not only a tactical move by the industry to comply with the circular economy principles but also an environmental necessity (Markevičiūtė & Varžinskas, 2022).

Green Plastics and Its Properties

Over the past few decades, bio-based polymers have reinvigorated their lustre owing to environmental issues, the exhaustion of petroleum resources, and consumers' preference for less harmful options. Presently, among the green plastics are different kinds of eco-friendly materials such as thermoplastic starch (TPS), produced by the plasticizing of native starch, polylactic acid (PLA), derived from corn starch, and polyhydroxyalkanoates (PHAs), synthesized by microbes through fermentation (Rahardiyan *et al*., 2023; Din *et al*., 2020).

The basic characteristics of a material determine its eligibility for being used as a biodegradable plastic. At least 50% of the material's weight must come from organic sources, and the level of heavy metals must be kept below the safe limits established. Under very precise environmental conditions, the material must degrade (almost 90% in six months). The degree of mineralization, which is the turning of organic matter into carbon dioxide (CO_2), is usually taken as an indication of the speed of biodegradation. Besides, the composting conditions, the commercial product should be reduced to minute particles of less than 2 mm in diameter over a maximum period of 12 weeks. It is very important that the final compost is free of any harmful substances and can be safely absorbed by nature in order to assure the product's ecological compatibility (Laycock *et al*., 2017).

Barrier and permeation properties

One of the most important factors in deciding the use and shelf life of biodegradable plastics for packaging applications. Such attributes are mainly the result of the material's chemical composition and the application's requirements since they specify the needed levels of resistance against permeation. In the main, plastic materials are differently permeable to small molecules like water vapor, gases, and organic liquids. During this, plastics have a very wide range of mass transfer characteristics from high barrier performance to low, which can be adjusted to specific food packaging applications. A comparative study comparing the barrier characteristics of traditional non-degradable plastics and suggested biodegradable materials substitutes gives a clear understanding of their differences in composition and possible application for food packaging (Fabra *et al.*, 2016). The insufficient barrier functionality will make the inner goods vulnerable to environmental impacts such as moisture, temperature variations, humidity, and oxygen, hence degrading the product quality. Usually, the rates of gas and water vapor transmission from the packaging material to the outside environment are regarded as the main criteria that decide the overall protective ability of the packaging system (Arrieta *et al.*, 2017).

Mechanical properties

Mechanical properties are very significant in deciding the performance and potential application of green plastics and bio-composites. Besides, these properties could be seen as the manner in which the material behaves when subjected to forces and stresses and thus help assess the material's life, strength, and suitability for the industry.

The tensile properties indicate the reaction of the material to stretching forces and denote its tensile strength, rigidity (Young's modulus), and elasticity. In fact, among the materials with a higher tensile strength the one that can accept a larger load before its complete failure is the material whose strength is the most crucial parameter for structural and load-bearing applications. The flexural properties, on the other hand, gauge the force required to bend a polymer and, therefore, tell us about the material's rigidity and the quality of the fibre-matrix bonding. This is of particular importance for products that may be subjected to either static or dynamic loads (Boey, J. Y. *et al.*, 2022).

The impact strength gives the information about the duration of the die or composite that the sudden shocks or impacts can be transmitted and thus the material would not be fractured. The tougher materials have impact strength which is higher and this is essential in areas like packaging, parts of the automotive industry, and safety-related components. The hardness of a material is an indication of its resistance to deformation, abrasion, and scratching, thus indicating its long-term durability and the wear it will suffer during its service (Boey, J. Y. *et al.*, 2022).

When taken together, these mechanical properties of green polymers are very elucidative of the performance and also help in the selection of materials for specific engineering, packaging, biomedical, and industrial applications. By studying the tensile, flexural, impact, and hardness behaviour, the researchers and manufacturers can increase the reliability of sustainable polymer solutions for modern industries by optimizing formulations (Boey, J. Y. *et al.*, 2022).

Thermal properties

The development of new analytical techniques has made it much easier to investigate the thermal properties of biodegradable plastics. If a packaging material is to perform well and to be of good quality, it must be thermally stable; this is important because packaging materials usually go through temperature changes at all stages from processing to storage and transportation. Thus, thermal behaviour assessment becomes an inevitable part of material characterization (Shah *et al*., 2017). Generally, thermal analysis is performed under carefully controlled temperature conditions such as room temperature (22-25 °C), low storage temperatures (like -18, -23, or -29 °C), and high ones (around 30 °C). The outcome of such analyses reveals very essential information about the heat transfer character of the packaging materials in steady state. To get comprehensive knowledge of the formulation, the processing parameters, the developmental characteristics, and the shelf-life performance of biodegradable plastics, Reis (2018) applied the standardized method ASTM D1525 and conducted thermal analyses of the plastics developing through the same.

Types of Biodegradable Polymers Used in Food Packaging

Polylactic Acid (PLA)

Polylactic acid (PLA) is one of the most promising and bioplastics recognized as the most widely used in the world. The overall process of making PLA starts with the fermentation of renewable raw materials, like corn, cassava, or sugarcane, which are classified as (Ncube *et al*., 2020). The lactic acid produced by the fermentation of these substrates is later converted into monomers and then into PLA. Among the bioplastics available, PLA has attained the greatest commercial appeal because of its outstanding properties like high transparency, rigidity, and ease of processing; thus, it is often likened to PET in terms of both appearance and performance (Din *et al*., 2020). Nevertheless, poor mechanical properties and low thermal resistance are the main disadvantages that limit its application to a very small area of hot temperature packaging. To tackle the weaknesses, often PLAbasically made up of natural fibers are used to reinforce and these could be lignin, cellulose fibers or starch for instance, the main advantages being not only the strength of the material but also the financial side (Ncube *et al*., 2020). Ultimately, in case of mixing with other antimicrobial or antioxidant compounds, PLA can turn into active packaging materials thus extending the duration of preservation and storage of food products (Maurizzi *et al*., 2022).

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) represent one type of bacterial polyesters that are produced via microbial fermentation under nutrient-limited conditions in most cases. The final result of this production is total biodegradability and biocompatibility, where all the films turn into water and carbon dioxide in aerobic environments (Din *et al*., 2020). However, thanks to the excellent barrier properties, the use of PHAs on a large scale is still limited because of the very high production costs which are mainly due to the complicated processes. Consequently, researchers are investigating the possibility of using agro-industrial residues and waste materials as alternative feedstocks to make PHA production economically feasible (Maurizzi *et al*., 2022).

Thermoplastic Starch (TPS)

Thermoplastic starch (TPS) is a biodegradable material that is considered as a potential bioplastic alternative due to its characteristics like wide availability, renewability, and total biodegradability. Plasticizing native starch granules with the agents such as glycerol or sorbitol at elevated temperatures results in flexible materials that are ideal for short-term food packaging applications (Rahardiyan *et al*., 2023). While these properties are advantageous, TPS has still limitations such as vulnerability to humidity and mechanical deformation. The application of advanced technology has developed TPS composite materials reinforced with fibers, chitosan, or nanoclay, which show very significant improvements in their mechanical strength and barrier properties.

Cellulose and Protein-Based Films

The usage of biopolymers obtained from natural sources like cellulose, gelatin, and soy protein for producing edible and biodegradable film coatings is getting more and more attention. They help protect the products by forming layers that not only enhance the resistance to permeation by oxygen and moisture but also permit the addition of natural antimicrobial and antioxidant substances (Maurizzi *et al*., 2022).

Green Bio-composites and Reinforcement Technologies

The combination of biodegradable polymers and natural fibers to produce the green bio-composites structures is a very important step towards the use of food packages that are environmentally friendly. Salwa *et al*. (2019) assert that the green bio-composites are composed of the natural fibers completely biodegradable materials, these fibers being the biopolymer matrices. The composites give the same benefits as the traditional production methods of plastics in terms of mechanical strength, thermal stability, and, more importantly, the water vapor barrier, while they still composted.

The most common plant sources of biodegradable materials are jute, hemp, rice husk, and banana fibers, among many others, which include agricultural by-products and wastes. Markevičiūtė and Varžinskas (2022) have pointed out that the plants that do not find any other use can be harvested for bioplastics, which not only helps in the development of bioplastics but also reduces agricultural waste. To be specific, wheat straw and sugar beet residues are very promising candidates for the use of biodegradable fillers in Europe and the Baltic region as that is the area of their production.

In addition, the use of certain nanocomposite techniques has improved the mechanical strength of the materials and their ability to kill bacteria and fungi (Maurizzi *et al*., 2022). Still, the potential migration of such nanoparticles into food products remains a lively regulatory and scientific concern.

Active and Smart Green Packaging

Modern green packaging is not a mere containment material any more, but it rather has active and vivid interactions with both the food and its ambient environment. Active packaging systems consist of oxygen scavengers, humidity controllers, or antimicrobials being periodically released which result in better food preservation and extended shelf life (Maurizzi *et al*., 2022). Unlike this, smart packaging merits the use of embedded sensors or visual indicators for tracing the freshness of the product and revealing the spoiling risk. Packaging materials based on biopolymers are more and more being blended with natural plant-derived additives like essential oils, polyphenols, and flavonoids to give them the properties of antioxidants and antimicrobials (Maurizzi *et al*., 2022).

Environmental and Economic Perspectives

Bioplastics allows us to lower carbon emissions and reduce dependence on fossil fuels. The overall impact of bioplastics on the environment is determined by the kind of raw materials used and the energy required for production (Ncube *et al*. 2020). In this case, the growing of specific plants for bioplastic production can take over food production land and consume large amounts of agricultural inputs while the use of agro-industrial waste as a source of bioplastics is a more sustainable and environmentally friendly option (Markevičiūtė & Varžinskas, 2022). Numerous LCA studies have reported that, in general, bioplastics emit less greenhouse gases than their petroleum-based counterparts. On the other hand, the biodegradation of bioplastics is greatly dependent on the landfill often, complete breakdown needs to be done in a facility capable of industrial composting (Rahardiyan *et al.*, 2023). Considering economics, the cost remains a huge obstacle as the price of bioplastics is about 1.5 to 3 times higher than that of conventional plastics (Din *et al.*, 2020).

Limitations and Challenges

Although there have been notable continuations in the green plastic industry, there are some key hurdles that could hinder its massive adoption:

1. **Mechanical and Thermal Constraints:** Biopolymers are still inferior to conventional plastics in terms of tensile strength, and their brittleness and thermal stability limitations are as well, which are the reasons why they are not used in high-demand packaging applications (Rahardiyan *et al.*, 2023).
2. **Moisture Vulnerability:** The mentioned materials, i.e., PLA and TPS, are prone to destruction by water vapor and hydrolysis, which can affect their physical and functional properties for the preservation of food (Din *et al.*, 2020).
3. **High Production Costs and Limited Scalability:** The production of biodegradable polymers, especially PHAs, is still a costly process because of the difficulties that are encountered during the microbial fermentation and purification processes (Ncube *et al.*, 2020).
4. **Inadequate Composting and Recycling Systems:** The controlled industrial composting environments are a must for the effective biodegradation of a number of bioplastics. Without these facilities, proper disposal is often the case and at the same time, the contamination of conventional recycling is occurring (Markevičiūtė & Varžinskas, 2022).
5. **Consumer Misunderstanding and Labeling Confusion:** The consumer confusion and difficulty in the proper waste sorting and management due to the ambiguousness of the terms “biodegradable,” “compostable,” and “bio-based” (Maurizzi *et al.*, 2022).
6. **Regulatory Inconsistencies:** The worldwide differences in the law and standards concerning biodegradability, labeling, and food contact safety have created obstacles for the eco-plastic industry's uniform adoption and market development.

Future Prospects

The advancement of green food packaging will rely heavily on continued developments in science, technology, and regulatory frameworks. Some areas of future focus are:

- **Bio-Nanocomposites:** The addition of nanoscale materials like nanocellulose, nano clay, or biochar to improve the mechanical properties and barrier efficiency of bioplastics has been researched.
- **Utilization of Agricultural Residues:** The various agro-industrial by-products, for instance, wheat straw, rice husk, and sugarcane bagasse, are being increasingly utilized as renewable and inexpensive raw materials for bioplastic production (Markevičiūtė & Varžinskas, 2022).
- **Microbial Process Optimization:** Enhancing PHA performance with the use of metabolic and genetic engineering while reducing production costs creates a potential opportunity in the future (Din *et al.*, 2020).

- **Active and Edible Packaging Films:** The production of multifunctional films that incorporate either antioxidants or probiotics along with food safety, quality, and retention period benefits (Maurizzi *et al*., 2022).
- **Circular Economy Implementation:** The European Green Deal and other sustainability strategies are supported by the promotion of closed-loop systems that allow for the effective recycling and composting of bioplastics.
- **Global Standardization and Labelling:** The proper introduction of global and universally accepted norms for the evaluations of biodegradability and their respective labels, which in turn would upgrade the clarity and confidence of the consumers.

Hybrid packaging systems that would mix biodegradable polymers with paper/plant-based fibers are the ones predicted to rise in popularity in the long run, as they will be the most environmentally friendly and will also have good mechanical properties (Markevičiūtė & Varžinskas, 2022).

Conclusion

The switch over to environment friendly and better biodegradable materials has made recycling of food packaging processes evolve to a great extent. Plastics made from natural resources like PLA, PHAs, TPS, and cellulose-based composites are among the green alternatives that are considered very promising responses to the ever-increasing environmental problems caused by plastic pollution. Material engineering, nanocomposite technology, and bio-based reinforcement have all contributed to the progress of biodegradable plastics to the point where they now display decent mechanical strength, excellent barrier properties, and functional versatility, which make them even more fitted for food packaging applications. Nonetheless, hurdles such as poor thermal stability, costly production, and lack of composting facilities for industrial use still limit their market penetration. To the world of green food packaging the future is innovation that combines sustainability with convenience. The use of agricultural waste, microbial fermentation, and bio-nanocomposite technology is a way to make materials that not only perform well but are also affordable.

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GREY PATCHES IN GREEN REVOLUTION: LEADERSHIP CHALLENGES IN AGRICULTURAL RESEARCH

BV Ramana Rao[1] and Surender Singh[2]*
[1]Founder Project Coordinator, AICRP on Agrometeorology,
ICAR - Central Research Institute for Dryland Agriculture, Hyderabad - 500 059, India;
[2]Senior Researcher/Professor - Agrometeorology,
Chaudhary Charan Singh Haryana Agricultural University, Hisar - 125 004, India.
*Corresponding Email: buverarao@gmail.com

The Green Revolution transformed India from a food-deficient nation to a global agricultural powerhouse. Yet, beneath this success lie systemic “grey patches” that undermine research institutions like ICAR and SAUs. The challenge is not the talent of scientists, but leadership structures and career frameworks that stifle innovation. Overemphasis on individual metrics - publications, patents, and grants - fosters competition over collaboration. Young scientists are marginalized, relegated to supporting roles, and denied opportunities for independent growth. Tenure-based leadership and administrative routines prioritize compliance over mentorship and succession planning. Gate keeping, patronage, and fear of being overshadowed further suppress bold, transformative research. These practices threaten institutional vitality, collective innovation, and the next generation of leaders. Reforms must redefine performance metrics, institutionalize leadership training, decouple recognition from patronage, and empower young faculty. Only through such systemic change can Indian Agriculture meet the challenges of sustainability, climate resilience, and global competitiveness.

The legacy of the Green Revolution remains one of India’s most lauded accomplishments—transforming a famine-prone nation into an agricultural success story. However, behind this celebrated narrative lie persistent "grey patches" that threatens to erode the very institutions that once powered this transformation: the Indian Council of Agricultural Research (ICAR) and the State Agricultural Universities (SAUs). The crisis is not rooted in a lack of scientific talent, but in a leadership and career advancement framework that suppresses innovation, disincentivizes collaboration, and neglects the cultivation of future-ready visionaries. Ironically, the performance metrics and administrative mechanisms designed to ensure accountability have become the very instruments stifling progress and undermining institutional vitality.

Power, Prestige, and the Perils of Performance

The University Grants Commission (UGC) guidelines, which shape career advancement schemes (CAS) across agricultural institutions, are anchored in quantifiable benchmarks—publications, patents, and externally funded projects. Though designed to uphold meritocracy, their implementation has inadvertently cultivated a culture of excessive individualism and transactional professionalism. Rather than fostering meaningful collaboration or long-term innovation, the system encourages strategic alignment aimed at ticking boxes, often at the expense of genuine scientific inquiry and institutional growth.

The Price of Prestige

The pervasive ‘publish or perish’ mandate has reshaped the priorities of agricultural scientists, compelling them to chase rapid-turnaround projects that generate multiple research papers -

often targeted at high-impact international journals, even if it means paying steep article processing charges ranging from 2,500 to 3,500 USD. This emphasis on quantity over quality discourages engagement with complex, long-term, and collaborative research essential for addressing the multifaceted realities of Indian agriculture. Career progression has become a solitary race, gauged by a scientist's ability to accumulate individual achievements.

This culture of individualism is further intensified by an overwhelming pursuit of awards, fellowships, and coveted committee positions. Attaining such recognitions frequently hinges not solely on merit, but on one's ability to "navigate power centres" - aligning research themes with prevailing institutional agendas, co-authoring papers with influential figures, and exhibiting unwavering loyalty to administrators who control nominations and patronage networks. In this environment, conformity often trumps critical inquiry.

As a result, scientists may gravitate toward politically safe, administratively popular research areas rather than venture into bold, disruptive, and high-risk inquiries that could drive transformative change. The relentless pursuit of personal visibility through strategic networking gradually erodes the spirit of collective endeavor. This hollowing of scientific collegiality poses a serious threat to the sector's capacity to address grand challenges such as climate resilience, nutrient-use efficiency, agroecological transitions, and rural sustainability.

The Cost of Neglected Talent

One of the most disheartening consequences of the current system is the systematic marginalization of young and emerging scientists. The very infrastructure that once catalyzed the Green Revolution now treats its fresh talent as mere cogs in sprawling administrative-research machinery. While senior faculty relentlessly chase publication quotas, project grants, and institutional accolades, early-career scientists are often relegated to supporting roles - tasked with data collection, lab work, statistical analysis, and manuscript preparation - indispensable contributions that remain largely uncredited.

Instead of being mentored to carve out their own research niche, secure pilot funding, or develop independent scientific profiles, their energies are siphoned off to serve the metric-driven ambitions of their seniors. Genuine mentorship is replaced by transactional delegation. In this pursuit of personal glory, senior scientists - preoccupied with securing awards, fellowships, and bureaucratic influence - have little incentive to champion the professional growth of junior colleagues.

This practice results in a dual loss. Institutions are deprived of the creativity, curiosity, and disruptive thinking that young minds bring, while the scientists themselves endure delayed recognition, diminished motivation, and professional stagnation. Over time, this breeds a sense of disillusionment, leading to a silent 'brain drain' from public research systems - either to administrative safe zones, the private sector, or out of science altogether. The system may make use of their 'legs,' but tragically, it chains their 'minds.'

The Leadership Vacuum

The leadership challenges in agricultural research institutions extend well beyond laboratories and field stations - they are deeply embedded in governance structures, particularly in the tenure system for managerial roles. Leadership positions, from Heads of Departments to Directors of institutions, are typically assigned for fixed, multi-year terms. While this system offers administrative continuity, it often fosters a mindset preoccupied with routine operations and the maintenance of status quo. The daily energy of these leaders is consumed by regulatory compliance, procedural documentation, and bureaucratic oversight, leaving little bandwidth for visionary planning - or more critically, for cultivating the next generation of leaders.

In this environment, leadership is reduced to efficient management rather than academic stewardship. The emphasis shifts from being a mentor and institutional strategist to becoming a custodian of files and meetings. As a result, the difficult but essential task of talent identification, delegation of strategic responsibilities, providing high-stakes exposure, and systematic leadership grooming is often neglected. When tenure concludes, institutions are left scrambling for a successor—frequently falling back on a familiar, risk-averse choice, thus perpetuating a cycle of predictable, uninspired administration.

Perhaps the most corrosive consequence of this system is the emergence of a protectionist leadership culture. Having reached the apex, some individuals use their authority not to elevate others, but to consolidate their own legacy. In such cases, institutional power becomes a tool for personal glorification—and the deliberate stalling of talented, younger scientists who might outshine them. This stagnation at the top suppresses innovation at the base and weakens the very future the system is meant to secure.

Barriers to Bold Leadership

Having successfully navigated the individualistic metrics and political undercurrents of the system, many institutional heads come to view their top positions not as platforms for collective advancement, but as the crowning achievements of their personal careers - stepping stones to honorary doctorates, national awards, and elite fellowships. Leadership, in such cases, becomes more about personal legacy than institutional transformation. This mindset breeds a culture of gate keeping. Access to critical opportunities—such as committee memberships, competitive funding, international collaborations, or meaningful administrative responsibilities - is often denied to promising young scientists who exhibit independence, originality, or the potential to challenge existing hierarchies. Rather than being nurtured, such talent is perceived as a threat.

To maintain control and avoid being overshadowed, incumbents may actively promote compliant individuals who pose no intellectual or strategic challenge. This ensures a docile next generation—one less likely to question, disrupt, or reform the system. However, such short-sighted leadership starves institutions of the very dynamism and bold vision required to navigate the future. At a time when Indian agriculture must pivot rapidly in response to climate volatility, global market shifts, and sustainability imperatives, this aversion to independent thinking represents not just a personal failure of leadership, but a systemic crisis of succession and renewal.

Forging the Future of Agricultural Research

From Grey to Green: Reforming Leadership for India's Agricultural Future

Overcoming these grey patches demands a systemic shift that places collaboration and collective growth above individualistic metric-chasing and political maneuvering. Institutional reforms must focus on fostering mentorship, teamwork, and forward-looking leadership.

1. Redefine Performance Metrics

Introduce evaluation criteria that reward *team science, effective mentorship, technology transfer with tangible impact, and inter-institutional collaboration.* Linking the performance of senior scientists to the growth and achievements of their junior colleagues would fundamentally transform the mentorship dynamic and encourage shared responsibility.

2. Leadership Training and Mentoring

Implement a structured, mandatory leadership development program for all middle- and senior - level faculty, emphasizing *strategic thinking, ethical governance,* and *succession planning*. Leadership should transcend routine administration, preparing the next generation to inspire, innovate, and transform institutions.

3. Decouple Recognition from Patronage

Establish transparent, peer-reviewed systems for awards, fellowships, and high-level appointments. By minimizing the influence of individual administrators and prioritizing genuine scientific impact, institutions can restore meritocracy and credibility in recognition.

4. Empower Young Faculty

Provide protected time and seed funding for early-career scientists to pursue independent projects. Make their success a Key Performance Indicator (KPI) for department heads, ensuring that nurturing young talent becomes an institutional priority rather than a discretionary act.

The Green Revolution was a triumph of technology and collective will. The next agricultural revolution -centered on *sustainability, resilience, and nutritional security* - will be a triumph of enlightened, reform-minded leadership. ICAR and the State Agricultural Universities must urgently transcend individual glory and administrative inertia, fostering a culture where the growth of the institution is inseparable from the growth of its youngest, brightest minds.

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TROPHIC GUILD CLASSIFICATION AS A FRAMEWORK FOR UNDERSTANDING FISH COMMUNITY STRUCTURE IN ESTUARIES

Shashi Bhushan[1]*, Dhalongsaih Reang[2], Harsha Haridas[1], Dayal Devdas[3] and Layana P[3]

[1]ICAR-Central Institute of Fisheries Education, Powarkheda Centre, Madhya Pradesh.
[2]ICAR-Central Institute of Fisheries Education, Kolkata Centre, West Bengal
[3]ICAR-Central Institute of Fisheries Education, Versova, Mumbai, Maharashtra, India
*Corresponding Email: shashi@cife.edu.in

Abstract

Fish feeding guilds are ecological classifications that group fish species based on their feeding strategies, diet composition, and trophic roles within aquatic ecosystems. Understanding these guilds is essential for ecological research, fisheries management, and conservation efforts. This review synthesizes current knowledge on fish feeding guilds, examining their classification criteria, ecological significance, methods of determination, and implications for ecosystem management and biodiversity conservation.

Introduction

Ecological communities are characterized by food webs, which are networks of species connected by direct links that represent energy transfers from producers to consumers. The different functional traits of a species like reproduction, nutrition, habitat utilization, and morphology have all been used to create guilds (Austen *et al.,*1994). A guild can be defined as the group of species which can utilise the similar category of resources in a comparable way (Root*,* 1967). In ichthyology, the concept of feeding guilds provides a framework for understanding trophic interactions, energy flow, and ecosystem dynamics in aquatic environments. The classification of fish into feeding guilds allows researchers to analyze community structure and predict ecological responses to environmental changes, such as habitat alteration, pollution, or climate change. To gain deeper insights into ecological functions, hierarchical structure, and connectivity within ecosystems, scientific studies have increasingly adopted a strategy of classifying fish species into specific categories or guilds (McLusky and Elliot, 2004). This approach allows researchers to analyse the functional aspects of the fish community structure, leading to a more straightforward understanding of complex ecosystems. By examining the contributions of different ecological guilds, the various ways in which fish species utilize diverse estuarine habitats throughout their life histories can be understood (Thiel *et al.,* 2003). Trophic guilds can be used in describing the functional role of species in their ecosystems (Franco *et al.,* 2008) and for identifying species that are most likely to compete for food resources (Specziár & Rezsu, 2009). The guild approach has the advantage of making community analysis simpler by acting as a functional link between different species and the community (Root*,* 1967). Trophic guild structure and dietary niche breadth of the fish communities are vital for understanding in order to identify the functional groups and the trophic interactions of constituent species that help in their coexistence (Gammanpila *et al.,* 2019).

Several tropical fish species have been observed to change their trophic guilds seasonally, and this shift can be influenced by either ontogenetic changes or variations in prey abundance throughout the year (Then and Chong, 2022). However, it is essential to consider that seasonality and ontogenetic shifts may overlap, making it crucial to distinguish between these effects. Properly understanding these complexities is vital for accurately studying and comprehending the dynamics of estuarine systems (Lee *et al.,* 2019). Diet overlap also influences trophic cascades, a phenomenon where changes in the abundance of one species can trigger a chain reaction of effects throughout the food web. Predation pressure from top predators on intermediate consumers can limit their population growth, indirectly benefiting lower trophic levels and promoting ecosystem stability.

Concept and Classification of Feeding Guilds

Fish feeding guilds are generally classified based on diet composition and foraging behavior. The most common categories include:

- **Herbivores**: Feed primarily on plant material, algae, or periphyton (e.g., *Tilapia zillii*).
- **Detritivores**: Consume organic detritus and decomposed matter (e.g., *Mugil cephalus*).
- **Omnivores**: Consume both plant and animal matter in variable proportions (e.g., *Cyprinus carpio*).
- **Planktivores**: Feed on zooplankton or phytoplankton (e.g., *Clupeidae* species).
- **Insectivores**: Consume aquatic or terrestrial insects (e.g., *Aplocheilus lineatus*).
- **Piscivores**: Predatory species feeding mainly on other fish (e.g., *Lates niloticus*).
- **Benthivores**: Feed on benthic invertebrates and organisms associated with sediments (e.g., *Catfish species*).

Some studies further refine these categories into microphages (feeding on small particles) and macrophages (feeding on larger prey items), or based on feeding habitats such as pelagic vs. demersal feeders.

The guild approach gives a significant advantage in simplifying community analysis by grouping together species that share similar roles or functions. The initial development of guilds within the context of fish inhabiting estuaries can be traced back to the early classical contributions of McHugh (1967) and Perkins (1974). These pioneering works involved the segregation of the various constituents of estuarine nekton into distinct ecological groupings. Additionally, the concept of guilds found application in the research of De Sylva (1975), who characterized groupings of estuarine fish according to their specific feeding tendencies and their role within the broader food web structure. This aggregation allows for the study of various crucial ecological concepts, such as functional diversity, community response to disturbances, and the dynamics of food web.

By categorizing species based on their ecological functions, researchers can gain valuable insights into the intricate relationships and behaviours within the community, providing a clearer understanding of its overall structure and function (Benoit *et al.,* 2021). Numerous functional guilds are available to categorize species based on their habitat preferences and vertical positioning within the water column (Elliott and Dewailly, 1995). Additionally, the Estuarine Use Functional Group (EUFG) offers a more comprehensive understanding of how various species utilize estuarine environments, providing valuable insights into their habitat utilization (Elliot *et al.,* 2007).

Methods of Determining Feeding Guilds

Several methods are used to determine fish feeding guilds:

1. **Gut Content Analysis (GCA)** – Direct examination of stomach contents provides insights into recent diet composition.

2. **Stable Isotope Analysis (SIA)** – Determines trophic position and long-term feeding patterns through $\delta^{13}C$ and $\delta^{15}N$ isotopic ratios.
3. **Functional Morphology** – Analysis of mouth parts, gill rakers, and digestive tract adaptations reveals feeding strategies.
4. **Field Observations and Behavioral Studies** – Provide qualitative data on feeding habits in natural settings.
5. **Molecular Approaches** – DNA barcoding of gut contents can accurately identify prey taxa.

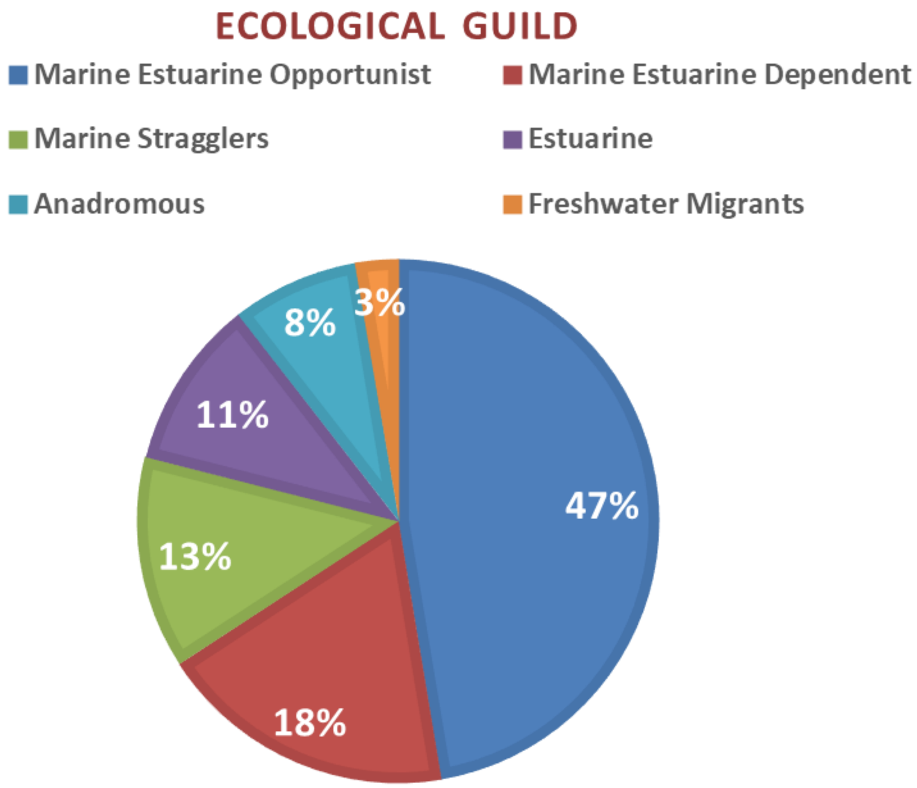

Figure: Ecological guild of Creek fishes, Mumbai Coast, India (Rajarshi *et. al.,* 2025)

Ecological Significance of Feeding Guilds

Feeding guilds play a crucial role in structuring aquatic food webs and maintaining ecosystem functions:

- **Trophic Dynamics**: Guilds represent different energy pathways and contribute to nutrient cycling.
- **Habitat Functioning**: Benthivores, for example, influence sediment turnover and oxygenation.
- **Biodiversity Indicators**: Changes in the proportion of feeding guilds often signal ecological disturbance or habitat degradation.
- **Ecosystem Resilience**: Functional redundancy within feeding guilds enhances the ability of ecosystems to recover from stressors.

Soe *et al.* (2022) studied the feeding habits and seasonal trophic guild structuring of fish community in the bay mouth region of Gulf of Thailand. They examined the feeding habits of 29 dominant fish species, characterized the trophic guilds, assessed the impact of season and clarified the role of diets in structuring the fish community. Most fishes were specialist feeders feeding on specific food components and were categorized into five trophic guilds: piscivore, shrimp-fish feeder, polychaete feeder, zooplanktivore and planktivore. Six species were piscivorous, considered as apex predators that fed almost entirely on fishes. High diet overlaps among some species (> 0.6) were recorded.

The abundance, migration, and growth of the fish are influenced by the availability of the food. A proper understanding of the feeding habits and diet of a fish species provides insight into the biology, physiology, and migratory pattern of the fish. The feeding habit of fishes greatly influences the trophic interaction and resource distribution in the ecosystem.

The feeding interaction and prey-predator relationship play a crucial role in trophic relationships, hence exerting a significant influence on the overall ecological balance of the environment. The migratory pattern of the fishes is directly or indirectly dependent on the feeding ground and breeding ground of the fishes. The feeding ground of the fish is again influenced by the local environmental parameters. The information on the feeding habits of the fishes also influences the fish harvest pattern, as different fishes prefer different types of bait.

Applications in Fisheries and Conservation

Understanding feeding guild composition aids in:

- **Fishery Management**: Identifying dominant trophic groups helps design sustainable harvesting strategies.
- **Habitat Restoration**: Guild-based assessments reveal ecological integrity and recovery progress.
- **Pollution and Impact Studies**: Shifts in feeding guild distribution can indicate eutrophication, sedimentation, or toxic contamination.
- **Climate Change Research**: Alterations in food availability may drive guild restructuring, influencing ecosystem productivity.

Current Trends and Future Research Directions

Recent studies emphasize the integration of **functional diversity** and **trait-based ecology** with traditional feeding guild analysis. There is growing interest in linking feeding guilds to ecosystem services, such as fisheries yield and carbon sequestration. Emerging technologies—like environmental DNA (eDNA) and machine learning-based trophic modeling—offer new opportunities for accurate guild classification. However, more research is needed to standardize guild definitions across regions and ecosystems.

Summary

Fish feeding guilds provide a vital framework for understanding trophic interactions and ecosystem functioning in aquatic environments. Their study bridges taxonomy, ecology, and conservation, offering insights into how communities respond to natural and anthropogenic changes. Continued interdisciplinary research combining morphological, isotopic, and molecular methods will enhance our ability to monitor and manage aquatic biodiversity effectively.

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IMPACT OF MONTHA CYCLONE ON FISHERIES AND AQUACULTURE

G. Vishwapriya, P. Ramesh*, P. Srilikitha, K. Nikhitha, K. Madhavi and R.R. Anupama

Department of Aquatic Environment Management, College of fishery science, Andhra Pradesh Fisheries University, Muthukur -524344, SPSR Nellore district, Andhra Pradesh, India.
*Corresponding Email: pramesh0301@gmail.com

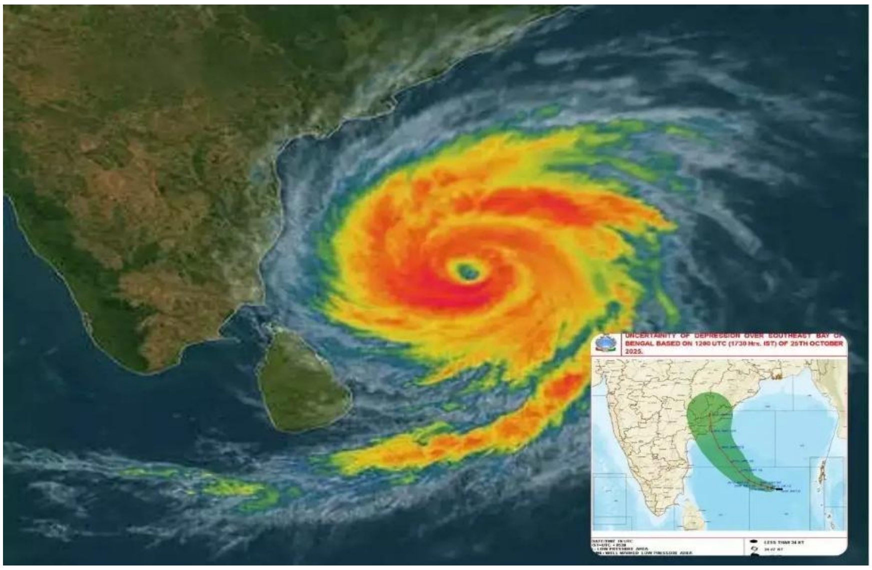
Abstract
Andhra Pradesh is a state with coastal districts in its south and south-eastern part and due to this; severe cyclonic events are very common in this state. Since last decade, Andhra Pradesh has experienced several cyclonic events among which cyclone were the last one that hit in December 2023. Cyclone has severe impacts on fisheries and aquaculture; it can alter hydrological parameters and habitat structure that led to change in fish species assemblage pattern, fish diversity and finally can put impact on local livelihood and food security. The present work was aimed to gather preliminary information on the impact of cyclone on fisheries and aquaculture in eastern part of Andhra Pradesh. The survey has showed post cyclone change in landing pattern with marine fishes contributed the major portion of the landing. Change in riverine fish diversity has also been observed with intrusion of brackish water species.

Keywords: Montha cyclone, freshwater, Brackish water, Mich Aung, Portunidae family

What is cyclone?
Cyclones are caused by atmospheric disturbances around a low-pressure area distinguished by swift and often destructive air circulation. Cyclones are usually accompanied by violent storms and bad weather.

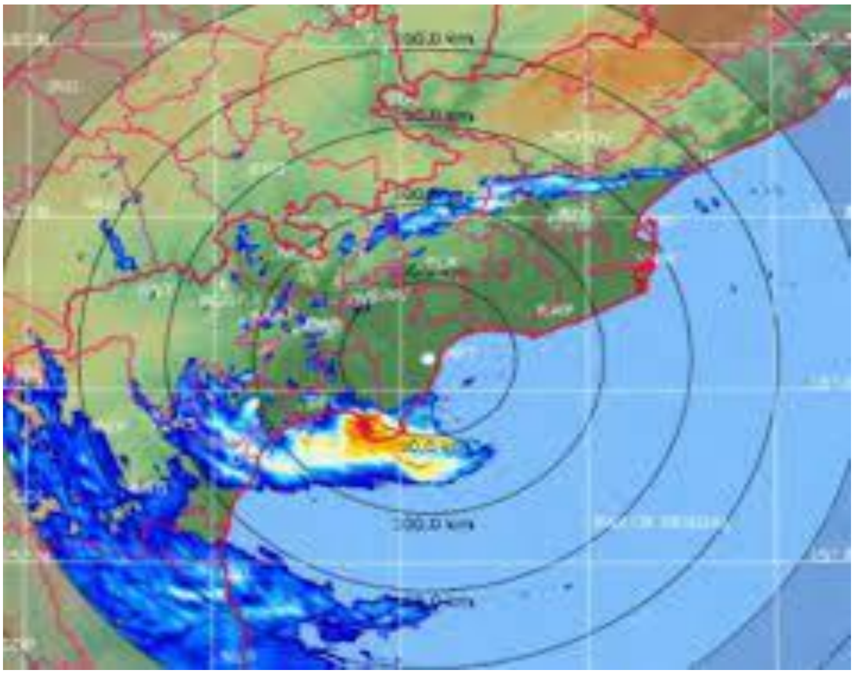
Introduction
Andhra Pradesh is a state of Eastern part of India which lies between 12°41' N to 19.07°N latitude and 77° to 84°40’ E longitude. The eastern and northern part of this state is facing Bay of Bengal; this state is having some coastal districts namely Kakinada, Visakhapatnam, Gopalpur, Nellore and some Tamil Nadu was also affected due to this cyclone especially Chennai which is near to Bay of Bengal. According to satellite imagery from the India Meteorological Department (IMD), cyclone Montha was located 480km east Chennai,530 km south-southeast of Kakinada, 560 km south-southeast of Visakhapatnam, 720 km south of Gopalpur (Odisha), and 890 km west of Port Blair. Since the last decade, Andhra Pradesh has experienced no. of cyclonic events, among which Mich Aung (hit in the month of December, 2023) and Gulab (hit in the month of September, 2021) are the two recent occurrences. Gulab was a kind of very severe cyclonic made more damage in both Andhra Pradesh and Tamil Nadu.

Effect of any cyclone is crucial as it imparts multiple variations in the physicochemical condition of the aquatic environment. Organisms like fishes are influenced by any changes in the aquatic environment and are extremely vulnerable to even minor changes in their ecological niche. Cyclones can have severe impacts on fisheries and aquaculture. Intrusion of saltwater in the river can enhance the salinity which can result in the introduction of some estuarine varieties and upstream movement of non-tolerant species. On the other hand, saltwater intrusion may result change in fresh water fish diversity as well as can impact on freshwater aquaculture. Cyclone can even result in food scarcity, livelihood income, and a lack of security.



Survey on fisheries

The survey work was conducted for the duration of one month (October 2025) post- Montha at Chennai (latitude 12.9° N and longitude 80.27°E), Kakinada (latitude 16.93° N and longitude 82.22°E), Visakhapatnam (latitude 17^o – 41′ and 17^o-59′ N and longitude 83^o – 12′ and 83^o – 27′ E) Gopalpur (latitude $19^0$18'13.44″N and longitude $84^0$57'52.72″E) Nellore (latitude 14.4426° N and longitude 79.9865° E) and the documentation was prepared based on fisherman's perception. For this purpose, questionnaire-based survey and focused group discussion were conducted. Around 150 active fishermen were integrated and interacted for the study.



Results and discussion

The post-Montha effect following the successive rainfall showed major discrimination of fish species both in terms of diversity and abundance. During the exploration, major fish species in landings were from marine ecosystem. Although, detail species wise quantification was not confirmed, data from Bapatla and Chirala region showed dominance of marine fishes especially, Penaeus vannamei, rohu *(Labeo rohita)*, Catla (*Catla catla*), and grass carp (*Ctenopharyngodon Idella*) are common in the region's freshwater resources. The annual production of Bapatla region is 2.19 lakh metric tons (MT) but due to Montha cyclone started from October 25-29 the fish ban was happened and there is no production of fish and prawn for these days.

And also, there is more fluctuations in pond make high mortality. This might be due to the change in water salinity and total dissolved solid (TDS) levels. Influx of marine water due to the cyclone in the estuarine region might have also changed the fish schooling pattern. The post Montha effect resulting in rainfall have caused in reduced water salinity levels thereby resulting in availability of brackish water fish species like Mugil cephalous, Liza tade, Lates calcarifer, etc. as observed riverine catch. It was also observed that more tolerant species, like crabs belonging to portunidae family like Scylla serrata, penaeid shrimps are survived with no such distributional effects from the cyclone. There was no such record of exotic fish distribution in the region.

Conclusion

This observation make me realised that there is more loss for not only Agri farmers also aquafarmers and that effects the pond fluctuations in its pH (due to the rain fall the farm may leads to decrease its pH because rain water contains low pH 5.5 to 6.5 so it leads to acidic condition), DO (due to no sunlight decrease in DO so the most highest mortality have been occurred especially at nights there is no power connections the aerators have been stop working and leads to mortality), salinity (it reduced suddenly and decreased).

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MODERN TRENDS IN MUSHROOM CULTIVATION FOR RURAL ENTREPRENEURSHIP

J. R. Patel[1*], K. J. Patel[2] and P. J. Kandoriya[1]

[1]Department of Agricultural Microbiology, N. M. College of Agriculture, NAU, Navsari, Gujarat, India
[2]Department of Agricultural Microbiology, B. A. College of Agriculture, AAU, Anand, Gujarat, India
*Corresponding Email: jhanavipatel6629@gmail.com

Abstract
Mushroom cultivation has become a promising avenue for rural entrepreneurship, especially in developing countries like India where agricultural waste is abundant and land resources are limited. Modern trends such as the use of improved substrates, controlled environment production, vertical farming, ready-to-fruit blocks, digital marketing, and value-added mushroom-based products are transforming this traditional activity into a profitable agribusiness. These innovations require low capital investment, generate high employment opportunities and offer year-round income, making mushroom farming an ideal enterprise for rural youth, women and self-help groups (SHGs). This article provides an overview of the latest technological trends, their advantages, challenges and opportunities for establishing successful mushroom-based rural enterprises.

Keywords: Mushroom, Rural entrepreneurship, Vertical farming

Introduction

Rural entrepreneurship is increasingly recognized as a powerful engine for economic growth, employment generation and livelihood security in rural communities. Among the various agri-based enterprises, mushroom cultivation has emerged as one of the most promising and rapidly expanding sectors due to its compatibility with locally available resources and low investment requirements. Mushrooms are highly nutritious, rich in proteins, vitamins, minerals and bioactive compounds, making them an ideal health-promoting food with steadily rising demand in both domestic and international markets. The cultivation process is simple requires minimal land and can be carried out throughout the year under controlled conditions. A major advantage is the ability to use abundantly available agricultural residues such as paddy straw, wheat straw, maize cobs, sugarcane bagasse, cotton waste and sawdust as substrates. This not only reduces production costs but also promotes sustainable waste management, making mushroom farming an eco-friendly, cost-effective and income-generating rural enterprise. (Sharma *et al*., 2024).

In recent years, mushroom farming has undergone a major transformation due to the adoption of modern technologies and scientific cultivation practices. The development of climate-smart and high-yielding strains has enabled year-round production even in regions with extreme temperatures. Affordable environmental control systems such as humidifiers, foggers and low-cost sensors have made it easier for rural farmers to maintain ideal growing conditions. Digital platforms now support training, marketing, and direct sales, reducing dependence on intermediaries. Additionally, value-added products like mushroom powder, snacks, pickles and nutraceuticals have increased profitability. These innovations are creating sustainable livelihood opportunities for rural women, small farmers, and unemployed youth (Malakar *et al*., 2025).

Traditional Mushroom Cultivation: A Background

Traditionally, mushroom cultivation was carried out in simple sheds or thatched structures where farmers depended entirely on natural temperature and humidity. During the monsoon season, species such as *Pleurotus* (oyster mushroom), *Volvariella* (paddy straw mushroom), and even *Agaricus bisporus* (button mushroom) were grown with minimal inputs. Although this method required very low investment, it faced several challenges, including strong dependence on seasonal climate, low and inconsistent yields, frequent contamination, and limited scientific knowledge among growers. These constraints restricted production to a small scale and prevented farmers from meeting market demand. Consequently, the need for reliable, year-round cultivation encouraged the adoption of modern, technology-driven techniques (Dutta *et al*., 2025).

Modern Trends in Mushroom Cultivation

➢ **Improved Substrates and Agro-Waste Utilization**

One of the most significant trends is the use of agro-industrial waste as a substrate. Materials such as paddy straw, sugarcane bagasse, groundnut shells and sorghum stalks are easily available in rural areas. Modern techniques include:

- Supplementing substrates with bran, gypsum and biofertilizers
- Pasteurization for contamination control
- Recycling spent mushroom substrate (SMS)

This not only increases yield but also promotes sustainable waste management and circular farming.

➢ **Climate-Smart and High-Yielding Mushroom Strains**

Research institutions have developed new mushroom strains that are:

- Thermo-tolerant
- Resistant to contamination
- Suitable for tropical climates
- Capable of producing higher yields

Examples include improved varieties of milky mushroom (*Calocybe indica*), oyster mushroom (*Pleurotus spp.*) and button mushroom (*Agaricus bisporus*). The introduction of medicinal mushrooms such as Shiitake (*Lentinula edodes*) and Reishi (*Ganoderma lucidum*) has opened new markets for nutraceutical and pharmaceutical industries. (Cheng *et al*., 2025).

➢ **Environmental Control Technologies**

Modern mushroom production increasingly relies on controlled environment techniques. Rural farmers now use:

- Automated humidifiers and foggers
- Low-cost temperature and humidity sensors
- Solar-powered exhaust fans
- GI or bamboo-based mushroom houses
- Insulated polyhouses

These technologies allow year-round production and reduce crop losses due to harsh weather. Affordable climate-control systems have made it possible for small-scale rural producers to grow mushrooms even in warm or dry regions.

- **Ready-to-Fruit (RTF) Blocks**

Ready-to-fruit blocks are pre-colonized mushroom substrates supplied by commercial spawn units. Farmers simply:

1. Cut open the block
2. Hang or place it on shelves
3. Maintain humidity

RTF blocks eliminate the need for substrate preparation, sterilization, and spawn running. This trend is particularly important for:

- Women self-help groups (SHGs)
- Rural beginners
- Part-time farmers

RTF technology has simplified mushroom cultivation to a level where even individuals with limited technical knowledge can generate income.

- **Vertical Farming Systems**

Vertical mushroom farming has become popular due to limited space availability in rural homes. Use of:

- Multi-tier racks
- Hanging bags
- Shelf-based units

allows maximum production per square foot. Vertical farming also enhances aeration and simplifies harvesting, making it highly suitable for small farmers (Gupta *et al*., 2024).

- **Organic and Chemical-Free Mushroom Production**

Consumers now prefer organic foods, and mushrooms grown without synthetic chemicals have high market value. Modern organic mushroom production involves:

- Use of natural disinfectants (neem, turmeric)
- Composting without chemical additives
- Biological pest management

Rural mushroom growers benefit from premium pricing and access to organic markets (Jha *et al*., 2023).

- **Digitalization and Smart Marketing**

Digital platforms play a crucial role in establishing rural mushroom startups. Farmers now use:

- WhatsApp groups for local sales
- Instagram and Facebook for online promotion
- E-commerce apps for direct marketing
- YouTube for online training and demonstrations

Digitalization enables farmers to reach wider markets, reduces exploitation by middlemen, and enhances profit margins.

➢ **Value Addition and Mushroom-Based Products**

Value addition is one of the most profitable modern trends. Popular mushroom products include:

- Mushroom powder (used in soups, bakery items, health supplements)
- Mushroom pickles
- Mushroom chips and snacks
- Mushroom nuggets, cutlets, and dry gravy mixes
- Mushroom biscuits and noodles

Mushrooms with short shelf life can be processed into long-lasting products, increasing earnings by up to 3-fold. Rural entrepreneurs can easily set up small processing units (Praveen *et al*., 2025).





➢ **Waste Recycling and Circular Economy Approach**

Spent mushroom substrate (SMS) is a valuable by-product used for:

- Organic manure
- Vermicomposting
- Soil conditioning
- Cattle feed supplement

This promotes sustainable agriculture and reduces waste, aligning with modern circular economy models.

4. Benefits of Mushroom Cultivation for Rural Entrepreneurship

Mushroom farming is ideal for rural entrepreneurship due to:

➢ **Low Investment and Quick Returns**

Small-scale cultivation requires minimal space, simple tools, and low-cost raw materials. Farmers can earn returns within 25–40 days.

- **Employment Generation**

Mushroom farming creates opportunities for:

- Youth
- Women
- Elderly farmers
- Seasonal labourers

- **Women Empowerment**

Women can easily manage mushroom production, packaging, and processing. SHGs are increasingly adopting mushroom farming as a group enterprise.

- **Year-Round Availability**

Controlled environment technologies allow continuous production throughout the year, ensuring stable income.

- **High Market Demand**

Mushrooms are popular in urban and semi-urban centers. The demand for fresh and processed mushrooms is continuously increasing.

- **Challenges and Practical Solutions**

Lack of Technical Knowledge
Solution: Skill development programmes, online training, Krishi Vigyan Kendras (KVKs).

- **Environmental Control Difficulty**

Solution: Low-cost mushroom houses, solar-powered fans, humidity sensors.

- **Marketing Issues**

Solution: Local branding, digital marketing, tie-ups with restaurants and vegetable shops.

- **Contamination Problems**

Solution: Proper hygiene, pasteurization, use of good quality spawn.

- **Government Support for Mushroom Entrepreneurship**

Many government agencies support mushroom startups:

- National Horticulture Board (NHB) – subsidies for mushroom units
- PMFME Scheme – support for food processing enterprises
- NABARD – loans and assistance for village industries
- ATMA & KVKs – training and extension
- State Horticulture Missions – technical and financial support

These schemes help rural entrepreneurs set up commercial mushroom farms or processing units.

Conclusion

Modern trends in mushroom cultivation are transforming this simple agricultural practice into a profitable and sustainable rural enterprise. Innovations such as improved substrates, vertical farming, climate-controlled units, ready-to-fruit blocks, digital marketing, and value addition have significantly increased productivity and income opportunities for rural communities. With growing demand, government support, and rising awareness of mushroom-based nutrition, mushroom entrepreneurship has immense potential to strengthen rural economies, empower women, and promote sustainable agriculture. The integration of technology and traditional farming practices ensures that mushroom cultivation will remain a key contributor to rural livelihood development in the coming years.

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ARBUSCULAR MYCORRHIZA: NATURE'S HIDDEN PARTNERSHIP FOR SUSTAINABLE AGRICULTURE

Suman Jayakumar Kankanwadi*, Karishma and Vijay Kumar

Ph.D. Scholar, Department of Microbiology,
Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana – 125004
*Corresponding Email: sumanjk2708@gmail.com

Abstract

Arbuscular mycorrhizal (AM) fungi, belonging to the phylum Glomeromycotina, form one of the most widespread and ancient plant–microbe symbioses, supporting nearly 80% of terrestrial plant species. These obligate biotrophs colonize plant roots and develop extensive hyphal networks that enhance the acquisition of essential nutrients, particularly phosphorus, nitrogen and micronutrients. Through a finely regulated exchange of molecular signals, AM fungi recognize host-derived cues, initiate hyphopodium formation, and establish intracellular structures such as arbuscules, which serve as the primary sites for nutrient transfer. The periarbuscular membrane and calcium-mediated signalling pathways in plant cells play crucial roles in coordinating symbiosis, gene expression and metabolic reprogramming. Beyond nutrient uptake, AM associations improve drought tolerance, soil structure, disease resistance and overall crop performance. Given ongoing challenges in agriculture including soil degradation and fertilizer dependency AM fungi represent an ecologically sustainable strategy to enhance soil health, crop resilience, and agricultural productivity.

Keywords: Arbuscular mycorrhizal fungi; plant–microbe symbiosis; arbuscules; phosphorus uptake; nutrient acquisition; molecular cross-talk; drought tolerance; soil health; sustainable agriculture.

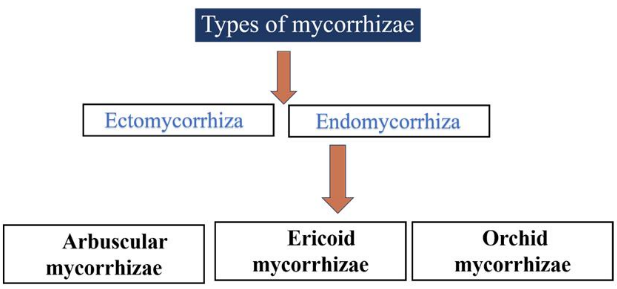
Introduction

In 1885, the German biologist and botanist Albert Bernhard Frank gave the name "mycorrhiza". Mycorrhiza comes from two Greek words 'myco' meaning fungus, 'rhiza' meaning root. True to its name, it describes a symbiotic relationship where fungi colonize plant roots. AM fungi are obligate biotrophs. Both partner's benefit:

- The fungus extends its network of thread-like structures (hyphae) deep into the soil, helping plants absorb water and nutrients more efficiently.
- The plant supplies the fungus with sugars produced through photosynthesis.

It's a classic example of "give and take" in nature. Hence, there is a bidirectional nutrient transfer between host plants and fungi (Ho-Plágaro and García-Garrido, 2022).

Types of Mycorrhiza



Characteristic Features of Arbuscular Mycorrhiza Fungi

- ✓ The mother of plant root endosymbiosis
- ✓ Living fossils - Arbuscular mycorrhizal (AM) fungi are considered remarkable due to their ancient origin, unique mode of life, and distinct genetics. They have persisted for over 400 million years with little to no change in their morphology, making them effectively "living fossils."
- ✓ Fungal species - 300
- ✓ Obligate biotrophic - An organism that is unable to complete a reproductive cycle in the absence of a living host
- ✓ Aseptate hypae - Not containing septae
- ✓ Coenocytic - Multiple nuclei within the same cell
- ✓ Anastomosis - A hyphal fusion with a cytoplasmic connection

Which Plants are Involved in Arbuscular Mycorrhiza Symbiosis?
Approximately 80% of terrestrial plants show symbiosis with Arbuscular mycorrhiza.

- ➢ Bryophyta
- ➢ Pteridophyta
- ➢ Gymnosperms
- ➢ Angiosperms
- ➢ Some mosses and lycopods

Amaranthaceae, Brassicaceae and Chenopodiaceae are non-mycorrhizal families

Stages of Arbuscular Mycorrhizal Symbiosis

The establishment of arbuscular mycorrhizal (AM) symbiosis occurs through a series of well-defined developmental stages. In the pre-symbiotic phase, the plant and fungal partners exchange molecular signals that enable mutual recognition. Following this communication, the fungus forms a hyphopodium on the root surface, creating the initial physical interface. Colonization then advances rapidly: the fungus penetrates the root using a pre-penetration apparatus (PPA), allowing entry into cortical cells where highly branched arbuscules are generated. These arbuscules are surrounded by the plant-derived periarbuscular membrane (PAM), which plays an essential role in regulating nutrient transport and signaling between host and fungus. The formation of storage vesicles and spores within the root marks the completion of the fungal life cycle. Effective establishment of symbiosis and nutrient transfer through arbuscules depends on precise molecular signal perception, downstream signaling cascades, and transcriptional reprogramming within plant cells (Shi et al., 2023).

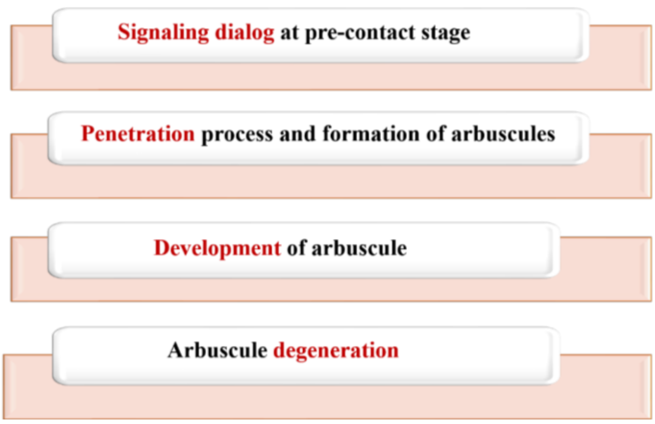


Figure 1: Stages of Arbuscular Mycorrhizal Symbiosis

As arbuscular mycorrhizal symbiosis advances, the fungus first detects the signals that the host plants emit, after which it secretes the appropriate Myc factors to communicate with the plants. By using surface receptors on the epidermal cells to distinguish between the Myc factors, the host plant starts the symbiotic cascade, which causes the nuclear membrane to release calcium and causes calcium oscillations in the perinuclear region. A nuclear-localized calcium and calmodulin-dependent protein kinase (CCaMK) decodes calcium oscillations, phosphorylates the corresponding substrates, and then triggers transcription factors to cause the expression of genes linked to symbiosis (Shi *et al*., 2023).

Why is Mycorrhiza Important for Agriculture Today?

Modern agriculture is facing challenges: declining soil fertility, overuse of chemical fertilizers, drought stress, and climate change. Mycorrhiza offers natural solutions to these problems.

1. Boosts Nutrient Uptake

Mycorrhizal fungi increase the effective root area by up to 100 times. This helps plants absorb:

- Phosphorus
- Nitrogen
- Micronutrients like zinc and copper

This means farmers can **reduce chemical fertilizer use** without affecting yields.

2. Improves Water Efficiency

The fungal network helps plants tap into water stored deep in the soil. This makes crops more **drought-tolerant**, an essential feature in a warming climate.

3. Enhances Soil Health

Mycorrhizae improve soil by:

- Increasing organic matter
- Enhancing soil aggregation
- Preventing erosion
- Supporting helpful soil microbes

A healthy soil means healthier crops—naturally.

4. Strengthens Plant Immunity

Mycorrhizal roots show greater resistance to:

- Root pathogens
- Soil-borne diseases
- Salinity stress

They act like a **biological shield** for plants.

5. Increases Crop Yield and Quality

Studies worldwide have shown yield improvements in crops. Mycorrhiza improves not just quantity, but also **nutritional quality**.

Table 1: Mycorrhizal fungal species with plant host

Mycorrhizal Fungi	Plants
Glomus versiforme, Glomus mosseae	Tomato
Glomus etunicatum	Maize
Acaulospora lacunosa	Strawberry
Rhizophagus irregularis	Wheat
Rhizophagus irregularis	Maize
Glomus mossae, Glomus geosporus	Strawberry
Rhizophagus irregularis	Tomato

Conclusion

Mycorrhiza is more than just a fungus; it is a **natural partner** that supports plant growth from the ground up. As agriculture moves toward sustainability, embracing mycorrhiza is like returning to nature's own toolkit for healthy soils, resilient crops, and improved productivity.

In an era where farmers seek eco-friendly solutions, **mycorrhiza stands out as a silent hero beneath our feet**, small in size but massive in impact.

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ORGANIC POULTRY FARMING: A SUSTAINABLE GROWTH PATH FOR ASSAM'S RURAL LIVELIHOOD INCOME GENERATION

Janmoni Shyam[1], Rafiqul Islam[2], Monosri Johari[3] and Kukil Saikia[4]

[1]Asstt. Prof., Dept. Of Extension Education, College of Veterinary Science, Khanapara
[2]Asstt. Prof., Dept. Of Poultry Science, College of Veterinary Science, Khanapara
[3]Asstt. Prof., Dept. Of Extension Education, College of Veterinary Science, Khanapara
[4]MVSc Scholar., Dept. Of Extension Education, College of Veterinary Science, Khanapara
*Corresponding Email: kukil.saikia.vmk24@aau.ac.in

Introduction

Assam, located in the northeastern part of India, is known for its fertile plains, rich biodiversity, and agrarian way of life. More than 70% of its population resides in rural areas, depending primarily on agriculture and allied activities for livelihood. Among these, poultry farming has emerged as one of the most dynamic and income-generating sectors.

In recent years, global awareness of food safety, animal welfare, and environmental sustainability has led to the rise of organic poultry farming. Due to the presence of numerous medications and pesticide residues in traditional products, there has been an increase in health concerns over the quality of egg and meat products. In organic poultry farming, birds are reared under natural scavenging conditions without synthetic inputs such as antibiotics, hormones, or chemical feed additives.

For Assam, where traditional small-scale mixed farming already exists, organic poultry farming presents an opportunity to blend traditional wisdom with modern sustainability principles. It holds the potential to transform rural livelihoods, ensure healthier food, and promote ecological balance.

Concept and Principles of Organic Poultry Farming

Organic farming is defined by the FAO as a distinct production management system that promotes and enhances the health of the agroecosystem, including biodiversity, biological cycles, and soil biological activity. Organic poultry farming is governed by the principles of health, ecology, fairness, and care, as outlined by the International Federation of Organic Agriculture Movements (IFOAM). It emphasizes the use of organic feed, ethical treatment of animals, natural disease prevention, and environmental conservation. With a focus on holistic health management and a biologically active soil, organic poultry farming strives to improve the health of the birds and environmental sustainability.

Key principles include:

1) Use of organic feed produced without chemical fertilizers, pesticides, or genetically modified organisms (GMOs).
2) Access to outdoor space to allow natural behaviors such as scratching, dust bathing, and foraging.
3) No routine antibiotics or synthetic growth promoters, relying instead on preventive health care and natural remedies.

4) Recycling of farm waste through composting of poultry litter, which enriches soil fertility.

These practices ensure that the system is environmentally sound, economically viable, and socially acceptable.

Why Organic Poultry Fits Assam?

1. Traditional mixed-farming systems

Farmers in Assam have long practiced mixed farming systems combining rice, fish, livestock and poultry. This traditional synergy makes organic poultry adoption easier, as farm waste can be recycled and feed can be partly sourced from within the farm itself (Saikia & Borah, 2023).

2. Rising demand for chemical-free food

With growing health awareness, urban consumers in cities like Guwahati, Dibrugarh, and Jorhat etc. increasingly preferring organic eggs and chicken. Nationwide, organic products command 20–40% higher prices, providing significant income potential for rural farmers (APEDA, 2024).

3. Government support and policies

The Government of Assam's Poultry Commercialization Policy (2024–25) aims to enhance poultry production and provide incentives for sustainable systems. Subsidies, training, and entrepreneurship schemes could be extended to organic ventures as part of broader livelihood programs (Department of Animal Husbandry & Veterinary, Assam, 2024).

4. Availability of Indigenous Breed of Poultry

Indigenous breed is already available in Assam which gives the scope for raising the poultry birds organically.

Practical Aspects of Organic Poultry Production

1. Breed selection

Indigenous and improved dual-purpose backyard varieties of chicken such as Kamrupa, Vanaraja, Gramapriya, Aseel, and registered chicken breed of Assam *viz*. Miri and Daothgiri (ICAR-NBAGR) are suitable for organic systems. These birds are hardy, disease-resistant, and well-adapted to local climatic conditions (ICAR-NER, 2023).

2. Housing and management

The fundamental goal of organic housing is to allow birds to express all their natural behaviour with little stress. The birds should have adequate protection from predators, access to sunlight, good drinking water, shade, and open spaces for exercise.Organic systems require adequate housing with natural ventilation and outdoor access. Birds should be raised in a deep litter system with the proper clean and dry bedding material. The floor of the chicken coop should be made of solid structure and covered with litter materials like straw, wood shavings, sand, and turf. In organic farming, an adult laying bird should have a minimum of 2 feet per bird in a confined space and 3 feet per bird in a foraging area, or 5 square feet per bird.

3. Feeding

Feed should come from certified organic sources or be home-produced using maize, broken rice, oilcakes, green fodder, and mineral supplements. Kitchen waste and locally available by-products can also be utilized after proper processing. The diet can be supplemented with vitamin and mineral supplements. As a source of protein, we can use organic peas, beans, and rapeseed. Peas can be added at a rate of 250-300g/kg for meat birds and 150-200g/kg for laying hens.

4. Disease management

Prevention is the key. Emphasis is placed on good sanitation, balanced nutrition, and herbal remedies. Vaccination is allowed in organic systems where necessary, provided documentation is maintained (FAO, 2022). In organic farming, growth promoters are strictly forbidden. Researchers' interest in the presence of various natural sub stances, such as medicinal herbs, as a new class of additives to animal and poultry feeds, has increased in response to the recent ban on the use of antibiotic growth promoters in poultry feeds. These additives have positive properties such as antioxidant, antimicrobial, and antifungal as well as immune modulatory and anticoccidial effect. Aloe vera, fenugreek, astragalus, moringa oleifera, cinnamon, tulsi, garlic, pepper, and other herbs have been provided by researchers. Herbal remedies are thought to be risk-free, affordable, eco-friendly, and without any side effects. They also help with digestion.

5. Waste recycling

Poultry litter is an excellent source of organic manure. Composting this waste reduces pollution and provides an additional income stream for farmers, contributing to a circular farming economy. Excreta and manure from organic poultry farm and its disposal are very easy in such a way that degradation of soil and water is minimum

Market and Economic Potential in Assam

According to the National Egg Coordination Committee (NECC), India's egg production increased from 114 billion in 2019–20 to over 140 billion in 2023–24. However, the organic segment remains below 1% of total production, offering untapped opportunities (NECC, 2024).

In Assam, per capita egg consumption (17eggs/year) is still lower than the national average (103eggs/year), highlighting both nutritional gaps and potential market growth (Department of Animal Husbandry & Veterinary, Assam, 2024).

Economic advantages

1. Premium price: Organic eggs can be sold for ₹10–12 per piece compared to ₹6-8 for conventional ones.
2. Low input cost: Reduced expenditure on synthetic medicines and chemical feed additives.
3. Employment generation: Backyard units can engage women and youth, promoting rural entrepreneurship.

Emerging markets

Urban centers such as Guwahati and Silchar are witnessing an increase in organic food outlets and online platforms. Local producer cooperatives can capitalize on this by forming Participatory Guarantee Systems (PGS) for group certification and marketing (PGS-India, 2023).

Challenges and the Way Forward

Despite its promise, organic poultry farming faces several practical challenges in Assam.

1. High certification cost

Formal organic certification can be expensive for smallholders. Group certification and local PGS models can help reduce these costs (APEDA, 2024).

2. Lack of technical knowledge

There is limited awareness of organic standards and management techniques. Regular training through Krishi Vigyan Kendras (KVKs) and veterinary extension programs is essential (ICAR-NER, 2023).

3. Feed availability
Sourcing organic feed ingredients is a major constraint. Promoting local organic feed production units could support small farms.

4. Market linkage
Farmers often lack access to organized organic markets. The creation of cooperative marketing systems and branding under "Assam Organic Poultry" could strengthen consumer trust and visibility.

Policy Recommendations
To realize the full potential of organic poultry in Assam, the following policy steps are recommended:

1. Integration into Assam's Livestock Development Policy, including financial assistance for organic certification and feed production.
2. Training and capacity building for farmers through government extension programs and NGOs.
3. Establishment of organic poultry clusters linked with existing organic vegetable and fish farming clusters.
4. Research support from institutions like AAU (Assam Agricultural University), CVSc (College of Veterinary Science, Khanapara), LCVSc (Lakhimpur College of Veterinary Science, North-Lakhimpur) and ICAR-NER, focusing on breed performance, feed formulation, and disease control in organic systems.
5. Marketing and branding support via the Assam Organic Mission and APEDA to connect farmers with premium markets.

Conclusion
Organic poultry farming offers a promising path for sustainable rural development in Assam. It aligns with the region's ecological conditions, cultural practices, and growing consumer demand for healthy food. By encouraging smallholder participation, providing training, and ensuring market access, Assam can position itself as a leader in organic poultry production in Northeast India. With proper planning and institutional support, this sector could play a crucial role in promoting food security, economic resilience, and environmental sustainability across the state.

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ORGANIC MANAGEMENT OF THE CHINESE FRUIT FLY (*Bactrocera minax*) IN MANDARIN ORANGE CULTIVATION

M. Soniya Devi[1*] and R. Yonzone[2]

[1]College of Horticulture, Central Agricultural University (Imphal), Bermiok Sikkim,
[2]College of Agriculture (Extended Campus), UBKV, Majhian, Dakshin Dinajpur,WB
*Corresponding Email: maimomsoniya.cau@gmail.com

Introduction

Mandarin oranges are among the most widely cultivated citrus fruits in Asia and are prized for their sweetness, aroma, and nutritional value. However, their production is significantly threatened by the Chinese fruit fly (*Bactrocera minax*), one of the most destructive pests of citrus orchards, particularly in China, Bhutan, India, Nepal, and other regions with suitable subtropical climates. *B. minax* is particularly damaging because of its unique life cycle; it is univoltine, producing only one generation per year, yet it causes widespread damage because its larvae feed deep inside the fruit, where they remain hidden and protected. Infested fruits drop prematurely, resulting in substantial economic loss. Traditionally, chemical insecticides have been widely used to combat fruit fly infestations. However, growing concerns over pesticide residues, environmental pollution, the development of resistance, and the rising demand for organic produce have increased the need for sustainable alternatives to synthetic pesticides. Organic management focuses on ecological principles, such as interfering with the pest's life cycle, enhancing natural enemies, maintaining orchard hygiene, and using non-chemical tools, such as trapping and botanical extracts.

This article provides an in-depth discussion of organic strategies for managing the Chinese fruit fly in mandarin orange orchards. It explores cultural, biological, mechanical, and botanical methods that align with organic farming standards and support the establishment of healthy orchard ecosystems.

Understanding the Pest: Biology and Vulnerable Stages

Effective organic control begins with an understanding of the pest's life cycle. The Chinese fruit fly progresses through four stages: egg, larva, pupa, and adult, each offering specific opportunities for intervention.

Life Cycle Overview

1. **Adult emergence:** Adults emerge from the soil during late spring to early summer, typically after sufficient soil moisture and warm temperatures.
2. **Mating and oviposition:** Females lay eggs under the rinds of developing fruits. This stage is highly critical because once the larva enters the fruit, it becomes very difficult to manage the infestation.
3. **Larval feeding:** Larvae feed inside the fruit pulp, causing internal rotting and premature fruit drop.
4. **Pupation in soil:** After completing larval development, mature larvae exit fallen fruits and burrow into the soil to pupate. They remain in the soil for several months, diapause over the winter, and then emerge the following year.

Organic management aims to break this cycle by targeting multiple stages: preventing egg-laying, eliminating larvae and pupae, and reducing adult populations.

Principles of Organic Management

Organic management is not a single method but an integrated system based on an ecological understanding. The core principles include the following:

- **Prevention:** Avoiding conditions that attract or support pest populations.
- **Monitoring:** Observing pest activity and determining when intervention is necessary.
- **Biological balance:** Using natural enemies and beneficial organisms to suppress pests.
- **Mechanical and physical barriers:** Preventing adults from accessing or damaging the fruits.
- **Non-synthetic inputs:** Application of botanical repellents, organic baits, and microbial agents.

These principles guide the following techniques in a coordinated, orchard-wide strategy.

Organic Techniques for Managing the Chinese Fruit Fly

1. Orchard Sanitation and Cultural Practices

Sanitation is one of the most effective and essential strategies. As larvae leave fruits and pupate in the soil, breaking this transition drastically reduces pest pressure in the following season.

Removal of Infested Fruits

- Regularly collect fallen fruits throughout the fruiting season.
- Infested fruits are destroyed by:
    - **Solarization:** Fruits were placed in sealed black plastic bags and exposed to direct sunlight for 3–5 days.
    - **Deep burial:** burying fruits at least 50–60 cm deep to prevent larvae from completing their life cycle.
    - **Composting with heat:** Using high-temperature aerobic composting methods.

Removing infested fruits prevents larvae from reaching the soil and significantly reduces the number of overwintering pupae.

Pruning and Canopy Management

Proper pruning improves aeration and sunlight penetration.

- Lower humidity levels discourage fruit fly activity.
- A well-managed canopy facilitates the spraying of botanicals and hanging of traps.
- Removing overly dense growth also reduces alternative shelters for adult flies.

Elimination of Alternate Hosts

Nearby wild citrus species and unmanaged orchards can serve as reservoirs for fruit flies.

- Wild host plants should be identified and removed within a radius of at least 500–1000 m.
- Encouraging community-level coordination to improve success.

2. Fruit Bagging: A Physical Barrier Method

Fruit bagging is a highly effective, residue-free physical method that is widely used in organic citrus production.

Timing and Method

- Bags were applied 40–60 days after fruit set when the fruits reached a suitable size.
- Use paper, cloth, or biodegradable bags that allow air exchange while blocking adult flies from entering.

- The bag was secured tightly around the fruit stem to prevent access.

Benefits Beyond Pest Control

- Prevents pesticide residue accumulation.
- It reduces sunburn and blemishes, improving fruit quality.
- It protects fruits from other pests, such as leaf miners and sucking insects.

Although labor-intensive, fruit bagging offers near-complete protection from oviposition and is ideal for smallholder and organic farming.

3. Organic Trapping Strategies

Traps are invaluable for monitoring and reducing the adult fruit fly population. Organic attractants and traps reduce the reliance on synthetic chemicals.

Protein Bait Traps

Adult female fruit flies are strongly attracted to protein sources such as yeast.

- Organic protein baits with yeast hydrolysate, jaggery solution, or sugar–vinegar mixtures should be used.
- Place the trap at mid-canopy height and checked weekly.
- Bait solutions should be replaced regularly to maintain effectiveness.

Protein traps specifically target gravid females, significantly reducing the egg-laying pressure.

Male-Attractant Traps

Although *B. minax* is less responsive to some male lures than other species, certain natural attractants can reduce male populations, thereby limiting mating success.

Yellow Sticky Traps

Yellow chromotropic traps exploit the natural attraction of fruit flies to bright yellow surfaces.

- This is useful for detecting the onset of adult emergence.
- It also reduces adult densities when used in combination with bait traps.

The integration of several types of traps offers a better chance of lowering the overall adult numbers.

4. Biological Control: Harnessing Natural Enemies

Biological control is central to organic pest management and involves the use of natural predators, parasitoids, and pathogens to control pest populations.

Parasitoid Wasps

Several species of parasitic wasps attack fruit-fly eggs and larvae.

- *Fopius* spp. and *Diachasmimorpha* spp. parasitize fruit fly eggs or early larval stages.
- They reduce the survival rate of immature stages before damaging the fruit.

Encouraging these parasitoids through habitat management, such as planting flowering plants that provide nectar, enhances natural biological control.

Entomopathogenic Fungi

Fungal bio-pesticides such as:

- *Beauveria bassiana*
- *Metarhizium anisopliae*

These fungi infect adult flies and soil-dwelling pupae. They can be applied as soil drenches or foliar sprays and are compatible with organic farming standards.

Entomopathogenic Nematodes

Species such as *Steinernema* and *Heterorhabditis* can infect pupae in the soil.

- Apply during moist soil conditions to ensure nematode survival.
- They target the soil stages of fruit flies, reducing adult emergence in the following year.

Biological agents are especially valuable for long-term suppression and are safe for beneficial insects, humans, and the environment.

5. Soil Disturbance and Mulching Techniques

As *B. minax* pupates in the soil, managing the soil environment is a crucial strategy.

Shallow Tilling

Light tilling under the canopy exposes pupae to:

- Sunlight
- Predators such as birds and ants
- Desiccation

This reduces the number of pupae that survive to adulthood.

Organic Mulching

Applying thick mulch layers (10–15 cm) around the base of the tree can:

- Physical barriers should be created to prevent larvae from burrowing into the soil.
- Promoting beneficial microbial activity that accelerates pupal mortality.
- Maintaining soil moisture and supporting overall orchard health.

The combination of tillage and mulching disrupts the pupal stage and reduces pest pressure in the following season.

6. Botanical Extracts and Organic Sprays

Botanical insecticides and repellents are plant-derived substances permitted under organic standards.

Common Botanical Sprays

- **Neem oil (Azadirachtin):** disrupts feeding and reproductive behaviors.
- **Garlic extracts** repel adult flies and mask fruit odors.
- **Chili and ginger sprays** deterred egg-laying.
- **Citrus or lemongrass oil sprays** provide natural repellence.

These sprays must be applied during early fruit development and repeated during the peak of adult activity.

Advantages

- It is biodegradable and environmentally friendly.
- Safe for applicators and consumers.
- It is compatible with biological control agents.

Although not as potent as synthetic insecticides, botanicals contribute significantly when used as part of an integrated organic approach.

Integration of Approaches for Maximum Success

No single method can fully manage *B. minax*. Successful organic management depends on the combination of several techniques throughout the year.

- **Pre-season:** till soil, apply mulch, and release biological agents.
- **Fruit set stage:** Install traps, prune canopy, and begin repellant sprays.
- **Fruit development stage:** bag fruits, intensify sanitation, and maintain traps.
- **Post-harvest:** remove fallen fruits, till the soil again, and apply bio-agents.

Synchronizing interventions with the pest's life cycle ensures maximum impact and long-term sustainability.

Conclusion

The Chinese fruit fly is a formidable pest in mandarin orange cultivation, causing significant economic losses owing to its concealed larval feeding habits and soil-based pupation. However, organic management offers an environmentally friendly and consumer-safe alternative to the use of chemical pesticides. Through a combination of orchard sanitation, fruit bagging, organic trapping, biological control, soil disturbance, mulching, and the use of botanical repellents, farmers can effectively disrupt the pest's life cycle and maintain fruit-fly populations at manageable levels. Organic practices not only protect crop yield but also enhance soil health, promote biodiversity, and meet the growing global demand for residue-free products. By adopting these integrated strategies, mandarin orchards can achieve sustainable pest control, improved fruit quality, and a long-term ecological balance.

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PROTECTED CULTIVATION: THE SMART WAY TO BEAT CLIMATE EXTREMES

Shivaraj Kumar Verma

Assistant Professor, Department of Horticulture,
Udai Pratap (Autonomous) College, Varanasi
Corresponding Email: shivraj.vns@gmail.com

Introduction: Farming Under Uncertain Skies

Indian agriculture has entered an era of climate unpredictability. One season brings devastating heat waves, the next brings torrential rains or unexpected hailstorms. The traditional open-field system, though rich in heritage, is increasingly vulnerable to these weather shocks. As farmers struggle to protect their crops from scorching temperatures, erratic monsoons, and pest outbreaks, a quiet revolution is emerging as protected Cultivation.

Protected cultivation is a climate-smart way of growing high-value crops using structures like greenhouses, shade nets, poly houses, and low tunnels. It allows farmers to control growing conditions, improve quality, save resources, and ensure year-round production. This article explores how protected cultivation is reshaping Indian horticulture and offering a powerful shield against climate extremes.

Protected Cultivation:

Protected cultivation refers to growing crops inside engineered structures that shield them from adverse weather and allow controlled application of water, nutrients, temperature, and humidity.

Common protected structures include:

- Polyhouses (naturally ventilated or fan-and-pad)
- Greenhouses
- Shade net houses
- Insect-proof net houses
- Low-cost poly tunnels
- Walk-in tunnels
- Hydroponic and vertical farming units

These structures create a microclimate that supports optimal crop growth, regardless of external weather conditions.

Need of Protected Cultivation in India:

Climate extremes have become the “new normal” in India. In the last decade, farmers have faced:

- Record-breaking heat waves in North India
- Unseasonal rains damaging tomato, grapes, mango
- Severe droughts in Vidarbha, Telangana, Karnataka
- Cyclones hitting coastal states
- Frost and hailstorms in the North-West

Benefits:

- Shields crops from heat, cold, wind, frost, hail & heavy rain
- Allows offseason production and fetches premium prices

- Saves 30–60% water through drip irrigation
- Ensures uniform, high-quality produce
- Reduces pest/disease incidence
- Enables high-density planting and higher yields
- Increases farmer income 3–10 times (depending on crop and structure)

Protected Cultivation Beats Climate Extremes:

1. Temperature Control

Poly houses and greenhouses maintain a stable temperature even during heat waves or cold spells.

- In summer: shade nets & ventilation reduce temperature
- In winter: UV film traps heat, reducing frost damage

This controlled climate is ideal for sensitive crops like capsicum, cucumber, strawberry, and flowers.

2. Rain & Hailstorm Protection

Unseasonal rains often wash away pesticides, spread fungal diseases, ruin fruit set, or physically damage plants. Protected structures shield crops completely no matter what the monsoon does. Hailstorms that destroy entire vegetable fields overnight cause minimal damage in protected units.

3. High Humidity Regulation

Fan-and-pad systems, foggers, and drip irrigation maintain ideal humidity levels, preventing:

- Blossom drop
- Fruit cracking
- Fungal outbreak

Hydroponics and vertical farming allow precise control over micro-humidity.

4. Wind Protection

Strong winds can uproot seedlings, break stems, and reduce yields.
A simple insect-proof net house can reduce wind stress by 60–80 %.

5. Pest & Disease Management

Protected cultivation significantly lowers pest entry using:

- Insect nets
- Double-door entry
- Sticky traps
- Microclimate regulation

Chemical sprays reduce drastically, encouraging safe and residue-free production.

Types of Protected Cultivation Systems in India

1. Naturally Ventilated Poly houses

- Made of GI pipes and UV film
- Cost-effective
- Best for vegetables (capsicum, tomato, cucumber)

2. Fan-and-Pad Greenhouses

- Advanced cooling system

- Suitable for very hot regions
- Ideal for flowers (rose, gerbera, carnation)

3. Shade Net Houses
- Reduce sunlight intensity
- Great for nursery raising, leafy greens, orchids

4. Insect-Proof Net Houses
- Excellent for virus-sensitive crops like tomato & chilli
- Major tool for IPM

5. Poly Tunnels
- Low-cost option
- Good for melons, leafy vegetables, and season extension

6. Hydroponics & Vertical Farming
- High-tech systems with soilless growing
- High yields in minimal area
- Suitable for urban and Peri-urban farming.

Crops Best Suited for Protected Cultivation

High-value vegetables:	Fruits	Flowers	Nursery plants
Capsicum (colour capsicum)	Strawberry	Rose	Vegetable seedlings
Tomato (indeterminate)	Blueberry (controlled environment)	Gerbera	Ornamental plants
Cucumber (slicing / Pickling)	Melons in tunnels	Carnation	Grafted saplings
Lettuce		Orchids	
Broccoli & exotic vegetables		Dutch cut flowers	

Conclusion: A Weather-Proof Path to Sustainability

Protected cultivation represents hope for Indian agriculture in an uncertain climate future. It empowers farmers to grow high-value crops safely, efficiently, and profitably regardless of heatwaves, storms, or rainfall variability.

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QUALITY ATTRIBUTES AND POSTHARVEST PRESERVATION STRATEGIES FOR FRESH TOMATOES (*Solanum lycopersicum*)

Nalanda Acharya
Research Scholar, Department of Pomology and Postharvest Technology,
Uttar Banga Krishi Viswavidyalaya, Pundibari, West Bengal-736165.
*Corresponding Email: nalandaacharya2018@gmail.com

Introduction

One of the horticultural crops that is grown and consumed extensively worldwide is the tomato (Lycopersicon esculentum). Tomato is rich in dietary fibers, phosphorus, iron, essential amino acids, minerals, vitamins, and sugars, which underscores its high nutritional value. From consumer perspective, visual appeal, firmness, taste, and dietary value are the attributes that determine the desirable properties of fresh tomatoes. Quality losses after harvest of tomato are attributed to a complex mix of physiological, pathological, microbiological, and mechanical processes. The rate of physiological processes such as respiration, transpiration and ethylene production markedly effect the rate of senescence in fresh tomatoes. Postharvest handling systems are designed to decrease the consequences of these degradation activities on the quality of fresh tomato. To preserve quality and lengthen storage life, management procedures including plucking, cleaning, sanitizing, initial cooling, sorting, and classifying, packing, storage, and shipping are crucial. Low temperature preservation, modified atmosphere packaging, 1- Methylcyclopropene, heating treatment, ultrasound treatment, UV-radiation, edible coatings are some of the techniques for physical preservation of tomatoes, while chlorinated water, oxonated water, electrolysed oxidizing water are chemical methods. The aim of this review paper was to x-ray the quality attributes of tomatoes, as affected by natural processes of its physiology, and postharvest preservation technologies for fresh tomatoes.

Impact of Postharvest on Tomato Fruit Quality

The commencement of postharvest period is marked by excision of tomatoes from its parent stock i.e., medium of its immediate growth. Postharvest continues during handling practices and stops when the food item is moved to final preparation stages toward consumption or further preservation (Nunes *et al*., 2008) Quality losses after harvest of tomato is attributed to a complex mix of physiological, pathological, microbiological, and mechanical processes. Postharvest handling systems are designed to decrease the consequences of these degradation activities on the quality of fresh tomato.

Physiological factors

Factors such as respiration, ethylene and transpiration affect to a very large extent the postharvest quality of fresh tomato. Like every other living plant, cells of tomatoes continue to exhibit arrays of biological processes after harvest. These activities continue from maturity, through ripening, senescence and finally culminate with death. Quality degradation happens due to the inability of the tomato cells to replenish energy and stored materials lost to biological process because it is detached from the paternal plant. The transpiration, respiration and C_2H_2 gas generation are the usual physiological events that leads to deterioration of fruits and vegetables.

At room temperature (20 – 25o C), tomato ripens quickly and consequently deteriorates rapidly. As a result of this knowledge, tomatoes are stored at cold conditions (< 12o C) to retard the physiological processes that accelerate decay. Chilling damage is among the main problems with the deterioration of tomato freshness. The longevity is shortened by these physiological defects and thereby limits the extent of application of cold temperature storge (Nunes *et al*., 2008) physiological elements including breathing, ethylene production, and water loss affect to a very large extent the quality of fresh tomato after harvest.

Respiration

Fresh fruits and vegetable maintain life by continuous utilisation of stored food (mostly carbohydrate) to produce ATP, which is a type of energy by process of breathing. As far as the leaves keep creating carbohydrates, the developing plant will always be respiring; it is impossible to halt this activity without harming the plants or the fruits and vegetable produce. Fresh fruits and vegetable cannot replenish carbohydrates or water once it has been harvested. Once stocks of accumulated carbohydrate or monosaccharides are depleted, respiration stops using them; as a result, the product ages and decomposes (Saltveit *et al*., 2019) Notably, tomato is climacteric in respiration patterns. This means that tomato experience peak in respiration during ripening and possesses the ability to ripen off and on plant. This increase in respiration rate that accompanied ripening caused degradation of stored materials in fruits leading to the ultimate death and quality deterioration of tomato (Kandasamy P, 2022) Pathogen attack, growth regulator, water stress, radiation and light are the types of environmental factors that impact the rate of respiration. The most relevant factors after harvest are physical stress, constituents of the atmosphere and temperature. The temperature of the storage environment is directly correlated to the rate of respiration within the physiological region of the commodity (Bachmann J and Earles R, 2000). To slow down quality deterioration caused by increased respiration; fresh tomatoes are subjected to cooling after harvest. Also, other atmospheric composition modifications were invented to decrease the speed of respiration and thereby prolong the storage period of fresh tomato (Rocculi P, 2006).

Transpiration

Like most fresh fruits and vegetables, fresh tomato contains 70-95% water. Owing to vapour pressure differential between the molecules of water interior the tomato and that in its environment, water inside the fruit evaporates to the surrounding leading to shrinkage, weight loss, loss of texture and crispiness (softening), and fading of appearance. This phenomenon resulting to loss of water by fresh tomatoes is referred to as transpiration and leads to wilting. To prevent this quality degradation process, the storage environment of fresh tomato is modified to drastically reduce or eliminate the vapour pressure differential amongst the internal and external environmental conditions of the commodity. This is done with adequate cognizance of the fact that occurrence of water deposition or condensation on the surface of the fruits would lead to proliferation of spoilage organisms and therefore balance must be struck in application of this principle for tomato quality shelf-life extension. The most favourable relative humidity during storage and distribution of tomatoes is 90 to 95%, while 75 to 78% relative humidity is most suitable for ripening.

Ethylene production

In fruit, the chemical regulator ethylene gas (C_2H_2) controls growth, maturation, and ageing. Climacteric fruits exhibit increased ethylene production as well as an upsurge in the breathing rate at the commencement of ripening. Tomato is a climacteric fruit and undergoes this transition process (Vijay P *et al.,* 2011). Increased ethylene production resulted to accelerated ripening and associated respiration rate, leading to rapid senescence, death, and decay. To increase the shelf life of tomato, activities that encourage excess ethylene production is avoided. Increase in temperature, incidence of injury and ripeness are the factors that favour an increase in ethylene gas production (Yahia and Brecht J K, 2012) Ethylene gas has both deleterious and beneficial effects on fruits and vegetables after harvest. These effects depend on a couple of environmental elements and physiological components. Advantageous effects of ethylene include promotion of the development of colour; stimulation of ripening process in climacteric fruit; promotion of citrus fruits degreening; stimulation of seed separation in nuts; alteration of expression of sex; promotion of flower formation, reduction of the permanent displacement of cereal stems from their vertical position (Iqbal *et al.,* 2017) Deleterious impact of ethylene includes acceleration of senescence; enhancement of too much softening of fruits; stimulation of loss of chlorophyll causing yellowing; stimulation of sprouting in potatoes; promotion of negative change of colour (discoloration) such as browning; promotion of dropping of leaves and flowers otherwise known as abscission; stimulation of metabolism of phenylpropanoid (Suzuki *et al.,* 2019).

Physiological Disorder

The physiological disorder resulting to postharvest tomato quality deterioration is chilling injury. It is an irreversible process observed in plant tissue that results from exposure of chilling-sensitive plants or fruits to temperatures below some critical. Tomato is very vulnerable to chill harm when exposed to temperature less than 12 to 13o C (Biswas P *et al*., 2016) As a tropical fruit, exposure to low temperature impacts tomato negatively. At temperatures below 10 o C, chilling injury occurs in ripe fruit. Also, chilling injury affects mature-green fruits below temperatures of 12.5 degrees. The effects of injury from cold temperatures of chilling are cumulative and it is directly proportional to time of exposure and temperature. At storage condition of 5 o C (41°F) and duration of more than 6 days, tomato fruit is damaged. Increased postharvest decay, off-flavour development, browning of seeds, water-soaked lesions, surface pitting, premature softening, and irregular colour development are the negative consequences of chilling injury on tomato fruits (NGMC/NARI, 2003) Tomatoes become weaker since they cannot continue their regular metabolic activities at relatively low temperature. In reaction to cold shock, many physiological and biochemical changes as well as cellular disorders take place in cultivars that are susceptible to cold (FAOSTAT, 2021).

Ultrasound Treatment

High amplitude wave usually above 20 kHz frequency represent the range of ultrasonic (US) fields. Ultrasound treatment is generated through mechanical vibration process in a medium. The particles of biological structure through which US propagated are subjected to compression and depression and this impact large amount of energy. Heating, cavitation, and mechanical actions employed in the food producing companies are used for cleaning with objective of disinfection of bacteria, and inactivation of virus and/or impaired cell covering of some microorganisms (Seymour I, 2002).Influence of postharvest ultrasounds treatments on tomato (*Solanum lycopersicum*, cv. Zinac) quality and microbial load during storage.It revealed that ultrasounds treatment was effectual in retarding development of colour and loss of texture, protecting tomato organoleptic quality, with rise of total phenolic compounds (TPC) and a decrease of load of microorganism. Due to the high frequency (20-100 kHz) at which ultrasound operate at, its power transmission needs liquid medium. Free radicals of hydroxyl and hydroxonium ions species and H_2O_2 can be formed if water is the medium for transmission. These free radicals possess beneficial bactericidal effects.

Emerging Technologies and Innovations

To prolong shelf life, lower post-harvest losses, and preserve nutritional content, several cutting-edge methods and techniques are being investigated for tomato preservation. Listed below are a few noteworthy instances: nanotechnology, pulsed electric field (PEF) technology, high pressure processing (HPP), cold plasma technology, smart packaging, and block chain technology. It is noteworthy that the extent to which these technologies are used may differ depending on variables including local tastes, financial concerns, and legal policies. Furthermore, many technologies' acceptability in certain markets may be influenced by ethical and safety issues, particularly those pertaining to genetic alteration.

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RECENT DEVELOPMENTS IN PATHWAYS REGULATING NATURAL BREEDING IN FINFISHES

Judes Ebin A*, S. Selvaraj , Ravibharathi S and R. Dinesh

Department of Aquaculture, Tamil Nadu Dr.J.Jayalalithaa Fisheries University,
Dr.M.G.R. Fisheries College and Research Institute, Ponneri, Thiruvallur, Tamil Nadu
*Corresponding Email: judesebin.a@gmail.com

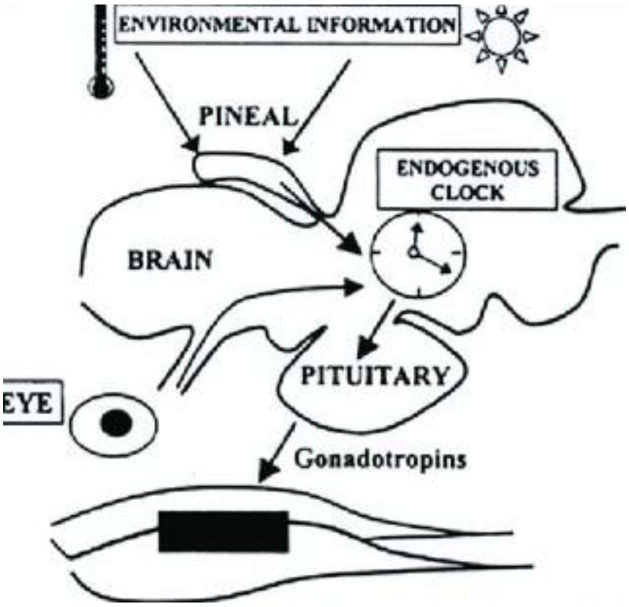
Introduction

Reproduction in finfishes is controlled by a complex, multilayered network that integrates environmental signals with internal hormonal and molecular pathways. This system, known as the brain–pituitary–gonad (BPG or HPG) axis; it coordinates how fish perceive external cues such as temperature, photoperiod, lunar cycles, and water flow to regulate the timing and success of spawning. In recent years, rapid advances in neuroendocrinology, molecular biology, and environmental physiology have reshaped our understanding of this process. New insights into neuropeptide systems including different forms of gonadotropin-releasing hormone (GnRH), kisspeptins (KiSS), and gonadotropin-inhibitory hormone have revealed how the brain integrates internal energy status and environmental information to modulate reproduction with remarkable precision. Simultaneously, the rise of "omics" technologies, functional genomics, and genome-editing tools has identified key genes and epigenetic regulators involved in gametogenesis, sex differentiation, and gonadal maturation. Understanding this pathway will promote breeding management in aquaculture and conserving wild fish populations.

Moreover, growing evidence links environmental stressors such as warming waters, altered photoperiods, and pollutants to disruptions in reproductive timing and neuroendocrine function. Collectively, these developments mark a transition from descriptive studies toward mechanistic and predictive science enabling both a deeper understanding of natural breeding rhythms and the potential for responsible manipulation of reproductive cycles in finfishes. Understanding the neuroendocrinological changes in natural fishes undergoing seasonal breeding is important in developing induced breeding methods for aquaculture and sustainable finfish seed production.

Seasonal reproduction in finfish

Seasonal reproduction in fish is directed by a endogenous rhythm or clock system, which operates on a yearly cycle and is synchronized with changes in daylight and time of year. This natural clock is synchronized, or entrained, by changes in daylength, known as photoperiod. Environmental cues, mainly light, reset the circadian clock every day to keep the fish's internal rhythms in sync with the 24-hour day. One major hormonal output of this system is the production of melatonin by the pineal organ, a key part of the timing system in fish. The pineal organ, located above the midbrain, is highly sensitive to changes in environmental light, and its photo neuroendocrine cells produce melatonin in response to these changes. Melatonin from the pineal organ affects different parts of the reproductive axis, helping to regulate puberty and the seasonal growth and maturation of the fish's gonads. In addition, cycles related to the moon and tides (lunar, semilunar, and tidal cycles) also play a significant role in determining the timing and frequency of spawning within a year. Recent studies indicate that melatonin can influence the brain's kisspeptin system, further helping to control the timing of seasonal reproduction in finfish.



Anatomical location of pineal gland in fish and its involvement in seasonal reproduction of finfish (Source: Francis *et al*., 2020)

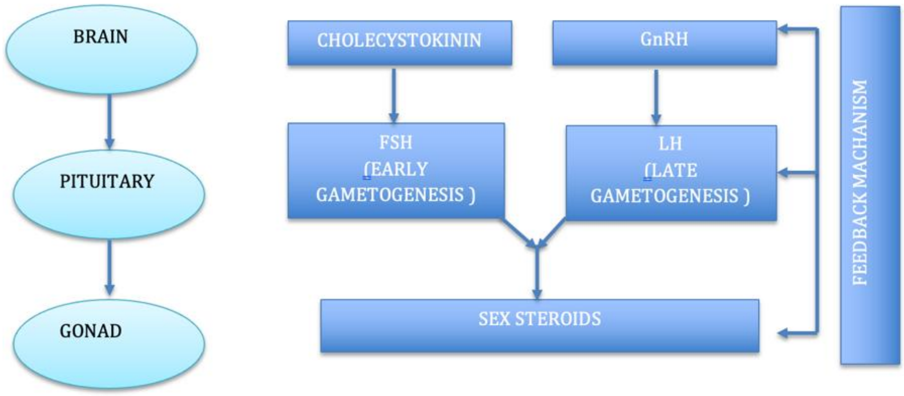
Role of GnRHs, GtHs and sex steroids in seasonal breeding

Gonadotropin-releasing hormone (GnRH) is produced in the brain and is delivered to the pituitary gland through neuronal axons. GnRH in the brain regulates both the production and release of pituitary gonadotropins, which include follicle stimulating hormone (FSH) and luteinizing hormone (LH). In most teleost fishes, FSH is mainly active during the early stages of gamete development, while LH takes a central role in the final stages, including spawning. The timing for increases in GnRH, FSH, and LH levels in different finfish species depends on ideal environmental factors such as water temperature and salinity, especially in tropical regions like India.

Specifically, an increase in LH in the blood results from heightened GnRH expression in the brain, which often happens during monsoon rains and changes in water currents. Greater levels of GnRH and gonadotropins (GtHs) cause a rise in circulating sex steroids. In males, the amounts of 11-ketotestosterone and 17α, 20β-dihydroxy-4-pregnen-3-one rise in the final phase of sperm development, while in females, estradiol-17β and 17α, 20β-dihydroxy-4-pregnen-3-one peak during the end of egg development and start of final oocyte maturation. During spawning, a surge in LH leads to increased 17α,20β-dihydroxy-4-pregnen-3-one, which is vital for successful mating and spawning under natural conditions. In aquaculture, hormonal treatments are used when natural hormone levels in the blood are too low and natural condition fail to stimulate gametogenesis. By analyzing steroid levels in the blood and reproductive dysfunction in the gonads, suitable hormone preparations are chosen and administered to fish to assist in successful breeding.

Cholecystokinin- A Recent discovery

Cholecystokinin (CCK) plays a critical and novel role in the natural breeding pathway of finfishes by acting as a primary regulator of the reproductive axis. In zebrafish, which serve as a key model for finfishes, CCK directly activates follicle-stimulating hormone (FSH) producing cells in the pituitary gland by binding to CCK receptors predominantly expressed on these cells. This interaction triggers calcium signaling that stimulates FSH secretion, which is essential for gonadal development and the progression of gametogenesis, ultimately leading to ovulation. Unlike the classic view where gonadotropin-releasing hormone (GnRH) was thought to control both LH and FSH, recent evidence shows that GnRH primarily activates LH cells, while CCK is the bona fide secretagogue for FSH cells. Mutation or disruption of the CCK receptor in fish severely impairs ovarian development and results in a complete shutdown of both FSH and LH secretion, demonstrating CCK's indispensable role in reproduction. This regulatory mechanism establishes a neuroendocrine link between nutritional status and reproduction, as CCK is also a satiety hormone, thus gating the reproductive process based on metabolic signals. Overall, CCK ensures that finfish reproduction is finely tuned to environmental and nutritional conditions, supporting successful natural breeding. It is likely that CCK neurons in the brain also mediate sex steroid feedback. Future studies on presence of sex steroid receptors in the CCK neurons need to be confirmed.

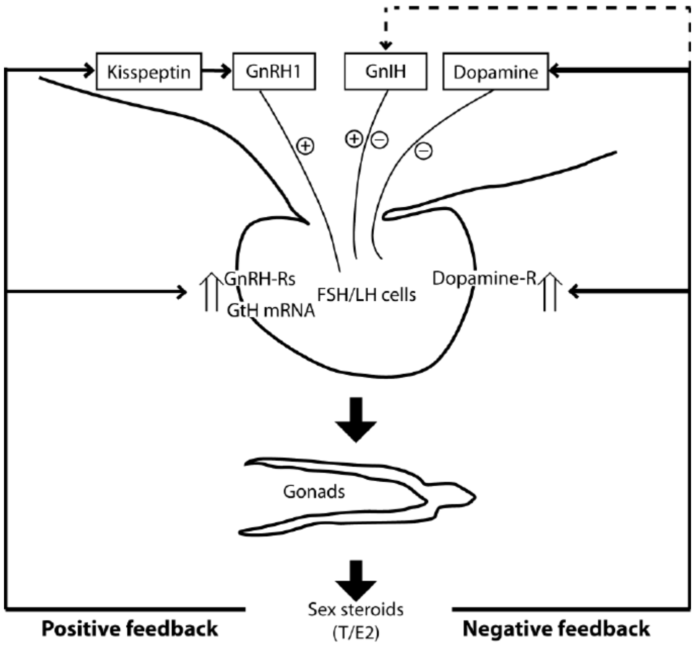


BPG axis pathway in fish

Steroid feedback mechanism in fish

The release of pituitary gonadotropins (GtHs) in fish is regulated through a negative feedback system where reproductive centers in the hypothalamus and pituitary respond to circulating levels of gonadal steroid hormones. In males, these steroid hormones mainly include testosterone, 11-ketotestosterone, and 17α,20β-dihydroxy-4-pregnen-3-one, while in females they include testosterone, estradiol-17β, and 17α, 20β-dihydroxy-4-pregnen-3-one. When circulating sex steroid levels rise, GtHs secretion decreases, thereby reducing steroid hormone levels to maintain balance. Conversely, a drop in steroid levels triggers an increase in GtHs secretion, restoring hormone balance through positive feedback.

This feedback loop is crucial for sustaining reproductive homeostasis in fish. Various neuropeptides contribute to regulating this negative and positive feedback system. In natural fish populations, this steroid feedback mechanism functions effectively to maintain hormonal balance and normal reproductive cycles. However, in cultured fish, disruptions in steroid feedback can occur at different levels, potentially impairing reproductive functions and breeding outcomes. This mechanism ties closely to brain-pituitary-gonad axis regulation, where hormones released in response to environmental cues like temperature and photoperiod synchronize reproductive timing and development in finfishes. Understanding and managing these feedback systems is vital in aquaculture for inducing and optimizing breeding performance. Cholecystokinin is a novel player in the feedback loop and an important element of reproductive BPG axis.



Schematic representation of negative and positive feedback in finfish
(Source: Kitahashi *et al.*, 2013)

Kisspeptin as novel regulator of steroid feedback in fish

Kisspeptin is a neuropeptide hormone belonging to the RF-amide family that acts as a key upstream regulator of the brain-pituitary-gonad (BPG) axis in fish. It plays an important role in mediating gonadal sex steroid feedback within the hypothalamus. In fish species such as medaka, kisspeptin neurons located in the nucleus recesses lateralis (NRL) of the hypothalamus are responsible for controlling sex steroid feedback. Similar roles have been shown in zebrafish and goldfish. Experimental administration of synthetic kisspeptin peptides in cultured finfish has been found to influence steroid feedback mechanisms and promote gamete development. Specifically, in medaka, the kisspeptin neurons that respond to steroids mediate the positive feedback effects of estradiol on reproductive processes.

Hormonal feedback loops in seasonal fish breeding

Melatonin is a hormone produced by the pineal gland in fish that plays a central role in regulating seasonal reproduction. It is released in a rhythmic pattern that corresponds to the light-dark cycle, providing the fish with information about daylength and seasonal changes. Melatonin acts on the brain-pituitary-gonad (BPG) axis primarily by influencing the hypothalamus and pituitary, which control the secretion of reproductive hormones like pituitary gonadotropins. This enables fish to synchronize seasonal reproduction with favorable environmental conditions. Besides its hormonal role, melatonin is also a powerful antioxidant that helps to reduce oxidative stress during oocyte maturation and spawning. Its actions are mediated through specific melatonin receptors found in reproductive tissues. While melatonin generally acts as a signal of darkness, its effects on reproduction can vary among species, stimulating or inhibiting gonadal development depending on the fish's reproductive status and environmental context.

In conclusion, a basic understanding of natural breeding is essential to formulate novel inducing agents for successful captive maturation and spawning of aquacultured fish. In recent years, due to climate change cultured fish experience different types of non-conducive environmental conditions which would result in failure of fish to undergo seasonal reproduction. In light of the above, it is essential to understand the different aspects of natural breeding. Though several studies have evaluated the involvement of GnRH in seasonal reproduction more studies on function of Cholecystokinin in seasonal reproduction are required to confirm the dual neuroendocrine regulators in seasonal reproduction in fish. Also, there is possibility that similar switches may operate in shellfishes like crustaceans and molluscs.

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INTELLIGENT PACKAGING FOR COLD CHAIN MONITORING IN DAIRY AND MEAT INDUSTRY

Mohd Abbas[1], Akash Deep Shukla[2], Sweta Rai[2], Aman Pal[1], Aditi Sharma[1] and Puspendu Nayak[1]

[1]Department of Post-Harvest Process and Food Engineering,
College of Technology, GBPUAT, Pantnagar, Uttarakhand, India
[2]Department of Food Science and Technology,
College of Agriculture, GBPUAT, Pantnagar, Uttarakhand, India
*Corresponding Email: Abbasmohd525@gmail.com

Abstract

A cold-chain system is a must for the storage and distribution of temperature-sensitive foods, like meats and milks, and their quality and safety too. A minimal change in temperature during the entire process of storage and distribution can support the fast growth of bacteria leading to financial losses. The conventional ways of packaging that does not allow the temperature, humidity, or any other important environmental condition to be known, through which it have been exposed. In contrast, intelligent or smart packaging comes with sensors, data communication tools, and responsive indicators that can continuously monitor, record, and in some cases even react to environmental changes. This explores the science behind and the new technologies that are going to come and the real-life applications of such systems for cold chain monitoring in dairy and meat products. It includes the use of the devices such as time-temperature indicators (TTIs), radio-frequency identification (RFID) tags, biosensors, and Internet-of-Things (IoT) and at the same time it deals with the problems like cost, standardization, and sustainability that are present. This article also looks at future technological advancements such as artificial intelligence, nanotechnology, and blockchain that can help improve food safety and sustainability along the supply chain.

Keywords: Intelligent packaging, cold chain, dairy, meat, RFID, biosensors, IoT, sustainability, blockchain.

Introduction

The management of the cold chain has turned into a crucial step of the food safety system as the chicken for the perishable goods and the complexity of the supply chains keep on increasing. Milk and meat, for instance, are among the most sensitive to temperature changes being that their high protein and moisture content make them ideal for bacteria propagation. Sooner or later, the temperature over 4 °C will cause spoiling and also the contamination of the food with pathogenic bacteria [1]. An FAO study has shown that approximately 30% of the global loss of perishable food is caused by poor temperature control during the handling and transportation. Traditional packaging materials like glass, paperboard, and plastic offer the physical protection but do not have the capability to sense or communicate the internal state of the food products.

A smart way to cope with this drawback is by the adoption of intelligent packaging, which integrates the sensing elements with the data communication systems that can continuously monitor the freshness, detect spoilage, and ensure traceability throughout the supply chain [2]. Intelligent packaging not only sustains the quality of the packaged goods but also plays a part in environmental sustainability by lessening waste, increasing energy efficiency in supply chain, and creating a customer who is more confident in the buying processes. The global call for digital food traceability has put such technological innovations at the forefront of the next-generation cold-chain management.

Intelligent Packaging: Working Mechanism

Smart packaging acts as an engaging system that can detect, log, and relay changes in either product or environmental conditions. It generally comprises three primary components:

1. **Sensor/Indicator Module:** Detects physical, chemical, or biological parameters such as temperature, humidity, or gas concentration.
2. **Data-Processing Module:** Converts raw signals into measurable values or visual responses through microprocessors or colorimetric reactions.
3. **Communication Module:** Displays or transmits data via visual colour change, barcode, RFID, NFC, or Bluetooth [3].

The main principle of signal transduction is the basis of intelligent packaging. A sensor turned environmental changes, for example temperature variations, into electrical or optical signals. After processing, this data can either be kept in a local storage or transferred to a monitoring platform through wireless communication. For example, a Time-Temperature Indicator (TTI) on a yogurt package could change color from blue to red when the amount of exposure has surpassed the safety limit, and at the same time, an RFID tag is recording digital data that can be accessed through a phone application.

The efficiency of an intelligent packaging system as a whole and its characteristics will be affected by several factors, such as the sensors` sensitivity and stability, production cost, and compatibility with food-safe materials. The latest research aims at the production of biodegradable polymer-based, printable and flexible sensors that can be produced on a large scale without compromising the accuracy of the measurements.

Major Technologies

Time–Temperature Indicators (TTIs)

A time–temperature indicator (TTI) ranks among the first and most extensively developed intelligent packaging types. It functions through chemical or enzymatic reactions, the rates of which are dependent on time and temperature. The total effect of these reactions is indicated by a colour change, which serves as a visual signal for the product's exposure to temperature variations throughout its shelf life [4]. For example: the meat and dairy industries largely rely on 3M MonitorMark® and Fresh-Check® stickers to indicate use-by or sell-by dates. Also, biopolymer-based TTIs employ natural pigments such as anthocyanins and curcumin which are not only eco-friendly but also have superb color stability.

The TTI devices are economically feasible and user-friendly, making them ideal for large-scale implementation. The only limitation is that the resulting data is qualitative, not quantitative; the device will only show that the product has undergone temperature abuse without specifying the exact conditions.

RFID and IoT-Enabled Monitoring

RFID technology, also known as Radio-Frequency Identification, utilizes electromagnetic fields for the automatic identification and tracking of items. RFID tags equipped with sensors can not only monitor but also register environmental conditions such as temperature and humidity as well as physical effects like vibrations or shocks. The integration with IoT systems allows the uploading of the gathered data to the cloud, where it can be monitored, analysed, and visualized in real time [5]. For example: Amul as well as other dairy cooperatives placed RFID thermistor fitted boxes to read the temperature continuously every few minutes. Another, RFID and GPS combination tracks meat from New Zealand to Europe and alerts when the temperature exceeds 5°C.

Automation, reduced manual inspections, and integration with enterprise resource planning (ERP) systems are among the advantages. Signal disruption in environments with metals or liquids and high tag prices are the two major issues.

Gas and Colorimetric Indicators

The spoilage process involves a slow but steady degradation of proteins and fats, which finally brings about the liberation of gases, in particular, carbon dioxide, ammonia, and hydrogen sulphide. Volatile compounds are the ones colorimetric sensors with pH-sensitive dyes are capable of detecting. In the case of such sensors, naturally derived pigments like beetroot and red cabbage extracts are commonly applied as safe and eco-friendly substitutes for synthetic colorants [6].

It follows the mechanism based on the reaction between the volatile amines and the dye changes the dye's molecular structure, thereby giving rise to a visible colour change that mirrors the degree of spoilage—usually moving from red to yellow or from blue to green. These sensors are most suitable for vacuum-packed or modified-atmosphere meat products. The dual-sensor films in some commercial versions are designed to detect simultaneously the oxygen leakage and the amine accumulation, thus offering a more comprehensive evaluation of the freshness of the product.

Biosensors and Nanotechnology Integration

Biosensors are the most sophisticated form of intelligent packaging technology. Specific compounds linked to food spoilage or contamination are sensed through biological recognition elements which can be an enzyme, antibody, or microbial receptor. A specific response which is usually in the form of electrical signal, light or colour change comes from the interaction of these elements and the target substances [7]. A typical biosensor comprises three main parts:

1. **Bioreceptor** – identifies and binds to a specific analyte (e.g., toxin, microbe, or enzyme).
2. **Transducer** – converts this biological interaction into a measurable signal.
3. **Signal Processor** – amplifies and interprets the data.

4. Applications in Dairy Products

Milk and Yogurt

Milk is considered to be the best candidate for intelligent packaging because of its short shelf life and high sensitivity to temperature changes. During collection, storage, and transport, TTIs and RFID sensors are generally deployed to track the temperature changes. Also, the cold chain's intactness can be easily checked visually through the use of colorimetric indicators that are directly applied to the milk pouches [8]. Lactic acid bacteria play a key role in producing the sour flavour of fermented dairy products such as yogurt, and at the same time, these bacteria are also responsible for the production of CO_2. Smart caps with CO_2 sensors can signal the retailers when the gas has reached an excessive level and the product has been over fermented. Continuous monitoring through the IoT-enabled RFID systems is the practice in some dairies, including Mother Dairy, that send mobile alerts when the temperature goes above 4°C.

Cheese, Butter, and Cream

Cheese and butter, for instance, during their storage, go through processes and changes that are metabolic such as lipid oxidation and enzymatic degradation. Gas or biosensors, which are integrated into the packaging films, can detect the volatile compounds that are released such as aldehydes and ketones. Butter wraps are coated with antimicrobial nanolayers and oxygen-scavenging coatings in order to improve their shelf life. The sophisticated IoT-enabled monitoring systems are advanced enough to bring together the different data sources, such as temperature, humidity, and gas composition to give the quality insights as a whole. The cloud-based platforms are now replacing the static “best-before” labels with the dynamic freshness indicators, thus allowing real-time shelf-life prediction. This data-driven method not only cuts down on waste but also improves inventory control and is in line with the principles of a circular economy.

Applications in Meat and Poultry Product

Fresh Meat Monitoring

The high protein content of fresh meat makes it very easy to get contaminated by microorganisms. During the spoilage of meat, the breakdown of protein results in the formation of biogenic amines like putrescine and cadaverine that are detectable through intelligent packaging systems. With the increase of these substances, the biosensors and colorimetric indicators that are integrated into meat trays display very clear colour changes [9]. In order to adhere to the food safety regulations, the temperature data during the transportation is continuously recorded and transmitted by RFID sensors. The Codex Alimentarius advocates the permanent temperature monitoring for the perishable exports which is now possible through smart packaging technologies. In the poultry logistics, the RFID containers equipped with thermistors are sending the real-time data to the centralized monitoring systems, thus enabling immediate corrective action whenever deviations occur.

Processed Meat and Export Logistics

Cold-refrigeration is a must for processed meat products like sausages, chicken nuggets, and frozen patties although they overall may be stored for a longer time. RFID and GPS technology integration allows for real-time tracking of location and temperature, while blockchain guarantees secure recordkeeping [10]. Smart labelling systems have been utilized by several European beef exporters, which enable the consumers and importers to check the whole cold-chain history just by scanning a QR code. The joint application of TTIs and RFID sensors offers a transparent and verifiable record of each lot’s storage and transport conditions.

Biosensor-Based Meat Quality Assessment

Present-day electrochemical biosensors are capable of detecting the spoiling process in merely a few minutes by identifying particular metabolites or bacterial toxins. One type of the sensor which is called amperometric sensors can give a quick and approximate product freshness by measuring electrical current fluctuation caused by bacterial respiration. Nanocomposite electrodes' superior sensitivity makes it possible to uncover microbial action before any spoilage signs become evident. Portable handheld readers equipped with bluetooth and used in conjunction with smartphones make it possible to evaluate meat quality right at the site of production, thus providing "farm-to-fork" digital verification and minimizing the requirement for traditional laboratory testing.

Sustainability and Environmental Concerns

The focus of future packaging technology is sustainability. Besides the reduction of waste and the improvement of safety for food, the environmental impact of these systems in the future is largely determined by the handling at the end of their life cycle and the choice of materials.

Eco-Friendly Materials

The usage of materials like cellulose, chitosan, and polylactic acid (PLA), which can be both biodegradable and bio-based, is becoming more common in the development of sensors by researchers. Natural pigments like anthocyanins and curcumin function as pH indicators and thus replace synthetic dyes which might be harmful to the environment. Films that are reinforced with nanocellulose are offering a solution that is both biodegradable and mechanically strong [11].

Waste Reduction and Circular Economy

Smart packaging systems help to reduce food spoilage which leads to less waste and indirectly lower emissions of methane and carbon from the disposal of food. The World Resources Institute (2022) claims that a 50% reduction in global food losses would mean an annual emissions reduction of about 8%, almost equal to the total emissions from other human activities throughout the global warming period. Thus, the intelligent packing is a direct contributor to the UN's goal of promoting the SDGs, particularly two of them, SDG 12 and SDG 13, namely, Responsible Consumption and Production and Climate Action, respectively. The circular economy concept has been pushing the product designers to adopt tactics that will make the materials and products more recycling, reuse and biodegrading friendly. For instance, the battery-free RFID systems using energy-harvesting technology are helping to bring about the complete cessation of electronic waste. Meanwhile, the biopolymer-based conductive inks used for sensors can be added to compost after their life cycle is over.

Energy Efficiency

IoT-connected refrigeration systems save electricity by adjusting compressor performance based on real-time sensor data. Furthermore, passive RFID tags and solar-powered data recorders are lowering cold storage's need on energy. Intelligent packaging is a key component of sustainable food distribution since it reduces both operating costs and environmental impact.

Challenges and Limitations

Although intelligent packaging has a lot to offer, it still faces some setbacks that are very practical in nature. Even after a long time considering the installation or maintenance of the RFID and biosensors, small-scale businesses are still being priced out of the market. Some environmental factors, such as humidity or pressure, may play negatively, becoming the source of inaccuracy of the sensor. Also, the merging of huge data sets from the IoT systems requires secure and interoperable platforms. Further, a significant number of consumers are still unaware of how to interpret smart labels. Moreover, the disposal of electronic parts in landfills is still a concern to the environment [12]. The overcoming of these setbacks requires that the packaging be made economically viable and eco-friendly through cooperation in R&D and state support.

Future Prospects

Future intelligent packaging for dairy and meat products will be data-driven automation and eco-friendly design. AI and Machine learning through analysing sensor data can give a better estimation of the remaining shelf life. If no tampering evidence is established, thus giving accurate records for regulatory audits. Bringing altogether TTIs, RFID, and biosensors into one system for extensive quality evaluation. Also, connecting smart labels via smartphones to show the freshness data will prove new age insights. From this small-scale enterprises will be able to benefit from the creation of paper-based RFID and biodegradable sensors [13]. These novelties that will lead to the democratization of intelligent packaging and thus make it available for use by both large scale and small-scale processors.

Conclusion

Intelligent packaging has changed the concept of food packaging from passive protection to active quality assurance. It not only combines sensors, indicators, RFID, and IoT connectivity, but also allows for real-time monitoring of cold chain and by doing so guarantees the safety of the most perishable products such as meat and dairy. This technology in addition to enhancing sustainability and reducing food waste there by giving consumer greater confidence and also being more compliant with international traceability standards. Smart packaging is going to be a key element in the transformation of the food sector's digital transformation as it makes way for smart cold-chain logistics. To make it through the economic and legislative barriers, collaboration among governments, businesses, and university researchers will have to keep on going. The intelligent packaging future is beyond human safety and sustainability it is going to produce data-driven food systems actually employing developed nanotechnology, artificial intelligence, and blockchain that both producers and consumers will benefit from.

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SAY GOODBYE TO YELLOWING IN GREENGRAM: NATURAL AND ECO-FRIENDLY SOLUTIONS FOR HEALTHY PLANTS

Sayani Das

Department of Agronomy, Faculty of Agriculture,
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur-741252, Nadia, West Bengal, India
Corresponding Email: sayani9916@gmail.com

Introduction

Yellowing of leaf is a common problem in greengram that significantly reduce photosynthetic activity, pod-setting and yield (Farhan et al., 2024). In greengram, yellowing of leaf can be managed with natural solutions that are environmentally sustainable and practical for farmers, rather than relying on chemical inputs. Yellowing associated with symptoms such as nutrient deficiency/mineral depletion, poor soil health, moisture stress, and pest/disease interactions can be reduced through natural methods. In the article, methods to assist soil health and nutrient uptake might include organic fertilizers, vermicompost, biofertilizers, neem cake, and safe cultural practices. Additionally, botanical sprays and biological controls will also help reduce whiteflies and the risk for Yellow Mosaic Virus (YMV). The article emphasizes sustainability and a holistic approach regarding prompt fertilizer application and treatment, moisture regulation, integrated pest management and use of safe substitutes while helping engender increased greenness, plant Vigor, and crop yield in greengram.

Few natural ways of preventing yellowing in greengram

- Improving soil health before sowing
- Seed treatment for healthy and disease-free germination
- Promoting root nodulation and biological nitrogen fixation
- Correct and balanced nutrient management
- Maintaining ideal moisture - preventing waterlogging and drought stress
- Mulching for moisture conservation and soil microbial activity
- Natural control of Yellow Mosaic Virus (YMV) and whiteflies
- Botanical and biological pest management
- Foliar sprays for enhancing chlorophyll and plant immunity
- Intercropping and maintaining proper planting density
- Crop rotation to break pest and disease cycles
- Timely weed management to control vector and nutrient competition

1. **Improve soil health before sowing:**
   Soil health prevents most yellowing related issues.
   - Apply well-decomposed FMY
   - Apply vermicompost
   - Apply neem cake that reduce soil borne pests.

   Soil containing adequate organic matter protects roots while enhancing nutrient uptake.
2. **Seed treatment -first step to disease-free growth:**
   When preparing the seeds, treat with one of them

- Rhizobium + PSB culture (biofertilizers)
- *Trichoderma harzianum* (biocontrol agent)

This combination aids in nitrogen fixation, mitigates fungal infection and supports uniform green growth.

3. Promoting root nodulation and biological nitrogen fixation:

- Make a single application of molasses–water solution after 20–25 days after sowing to stimulate Rhizobium activity
- Spray molybdenum (or apply ammonium molybdate at sowing) to support nodule function
- Nature's solution for nitrogen-deficiency yellowing

4. Correct management of nutrients:

Yellowing of leaves is often a sign of iron and nitrogen deficiency. Foliar sprays with solutions containing

- Urea or cow urine solution for nitrogen
- Ferrous sulphate + lime for iron deficiency

These natural inputs can restore greenness to leaves quickly

5. Preventing water logging and moisture stress:

Greengram is sensitive to excessive moisture and moisture deficiency.

- In branching and flowering stages, light irrigation would be required.
- Drainage should be managed after heavy rain.
- Avoid sitting in water for over 24 hours.

The moisture protective of the roots will reduce yellowing.

6. Mulching to conserve soil moisture and soil microbes:

- Apply crop residue mulch / straw mulch after 15–20 days after sowing
- After careful consideration of the trade-offs, will conserve moisture, reduce heat stress, and also improve beneficial soil microbes
- Nature's solution for drought and heat damage related yellowing

7. Natural control of Yellow Mosaic Virus (YMV):

Caused by the whitefly vector, YMV leads to sudden yellowing of the crop.

- Use YMV-resistant varieties (if they are available in the area).
- Install yellow sticky trap.
- Use neem oil spray to whitefly cover at 7-10-day intervals.

These methods will reduce the possibility of YMV spread without using chemical insecticides.

8. Use of botanical pest repellents in conjunction with the neem:

- Garlic–chilli–ginger extract
- Can use cow dung + buttermilk spray to suppress sucking pests and some mildly-fungal growth
- Nature's support for white fly reduction and YMV risk

9. Enhance plant immunity with bio-inoculants:

- Spraying Pseudomonas fluorescens (0.2%) or Beauveria bassiana suppression all-natural diseases

- Supports plant in keeping leaves healthy and green without spraying a synthetic fungicide

10. Foliar spray to provide healthy foliated naturally:

Spraying any of the following options improves leaf greenness.

- Panchagavya
- Jeevamruth
- Seaweed extract
- Humic acid

These bio-stimulants favour chlorophyll formation and will encourage a plant immune response.

11. Intercropping and proper planting density:

Overcrowding creates disease pressure and shading.

- Maintain optimum spacing for greengram
- Intercrop with sorghum/sesame to reduce whitefly attack and provide support for natural predators.

12. Crop rotation to break pest and disease cycles:

- Avoid continuous greengram cropping on the same land
- Rotating with rice, maize, sesame, mustard, or sorghum will help prevent pathogen and nutrient fatigue

13. Timely management of weeds

- Weed early to remove hosts of whitefly / thrips / mites.
- Weed early to reduce competition for moisture and nutrients. The stronger the green leaves, the less effects of virus carriers.

Table 2: Field success checklist for farmers

What to do	Purpose
Add FYM + vermicompost + neem cake	Healthy soil and roots
Seed treat with Rhizobium + PSB + Trichoderma	Strong, disease-free start
Molasses + molybdenum	Better nodulation and nitrogen
Mulching	Moisture and heat protection
Botanical sprays (garlic–chilli–ginger / cow dung mix)	Reduce whitefly and YMV risk
Pseudomonas / *Beauveria spray*	Natural disease and pest control
Crop rotation	Break pest cycle
Early weeding	Less pest hosts and competition
N + Fe correction (urea/cow urine + $FeSO_4$+lime)	Quick greening
Drain excess water + light irrigation	Prevent drought and waterlogging stress
Neem oil + sticky traps + resistant variety	YMV protection
Panchagavya / seaweed / humic acid spray	Improve chlorophyll and immunity
Maintain spacing + intercrop with sorghum/sesame	Less shading, less whitefly

Conclusion

The greengram leaves turn yellow not only one reason, there are multi-factorial causes, such as nutritional issues, soil health issues, moisture and pest–disease issues, etc. Farmers can successfully manage greengram yellowing with natural and environmental-friendly principles and practices that bolster the crop from the soil up, rather than just relying on chemical sprays. Practices such as incorporating organic manures, using biofertilizers, nodulation enhancement, mulching, timely irrigation, botanical extracts and biological pest management, as discussed, influence the leaf health as well as plant immunity overall. When these systems are combined with crop spacing, intercropping, crop rotation, and early weed removal, these practices facilitate environments where greengram grow vigorously with minor risks of Yellow Mosaic Virus (YMV), as well as other stresses. Therefore, following this more holistic principles and practices preserves greener leaves, reduces input costs, and increases yield and profitability in more sustainable and environmental-friendly ways.

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SEED DORMANCY: NATURE'S STRATEGY FOR PLANT SURVIVAL

Masoom Ankit Patel* and Sheetal Naik

Ph.D. Scholar, Department of Seed Science and Technology,
Odisha University of Agriculture and Technology, Bhubaneswar, Odisha
*Corresponding Email: masoomankitpatel@gmail.com

Abstract

The process of seed dormancy is an adaptive process that will not enable seeds to germinate until very favourable environmental conditions prevail. The phenomenon is an essential aspect of plant ecology, farming, and biodiversity. One can distinguish between the exogenous and endogenous, combinational and secondary type dormancy, which are regulated by the various physiological, morphological, or environmental factors. Hormonal regulation, particularly the balance between Abscisic acid (ABA) and Gibberellic acid (GA), plays the leading role in the induction of dormancy in seeds. Ecologically, dormancy increases the persistence of the species through seed banks and temporal dispersal. Agriculturally, in crop management, it poses both an issue and a challenge in handling the crops. To cultivate seeds, dormancy is incurred by different methods, including scarification, stratification, and hormone treatments. The relationship between seed dormancy and climate change/food security, sustainable agriculture, and the preservation of genetic resources is vital, as the manipulation and perception of this phenomenon are crucial. This paper reports on the existing information on the types and processes of seed dormancy, its ecological functions and utility, and the reasons it is significant across several industries.

Keywords: Dormancy, Scarification, Stratification, Gibberellic Acid, Thiourea

Introduction

Dormancy is one of the adaptations that enables plants to survive in unfavourable conditions. It is the condition of a viable seed under the condition that it fails to respond by germinating. Such an inability by nature promises not to allow the seeds to grow prematurely during the unfavourable period. Rather, dormancy provides that seeds have the best chance of survival because germination is synchronized to occur during favourable environmental conditions. Agriculture, ecology, and conservation biology depend on an understanding of seed dormancy. It has an influence on the storage of seeds, crop timing, and regeneration of species within the natural environments. Internal physiology factors, as well as external environmental factors, influence the dormancy phenomenon. Hormonal regulations, developmental stage of the embryo, etc., contribute to the physiological dormancy (Penfield, 2017). Environmental factors like increased temperatures during grain filling in crops can increase the levels of ABA in the seeds, resulting in dormancy (Onyango and Mwang'ombe, 2006). Dormancy does not last very long and is usually released when the seeds are stored under normal conditions. This article delves into the types, mechanisms, ecological significance, and practical implications of seed dormancy.

What is Seed Dormancy?

Seed dormancy is a state of inhibited germination despite the presence of favourable conditions of seedling growth. This condition is not a result of damage or death, but a survival technique that allows seeds to wait for the most favourable conditions to begin growth (Bewley *et al.*, 2013).

Dormancy is a crucial feature present in the seed, enabling it to survive better. It serves as an evolutionary buffer, helping plants to time their germination to increase the chances of seedling survival. And while beneficial to farmers and seed scientists, understanding how this delay mechanism works can lead to better seed preservation, storage and plant timing.

Types of Seed Dormancy

Researchers have classified seed dormancy into different types based on its cause and nature. The primary categories are:

1. Exogenous Dormancy: This type is caused by factors outside the embryo; usually, the seed coat or surrounding tissues are involved in inducing this type of dormancy.

- **Physical Dormancy:** A hard seed coat prevents water or gas permeability, thereby restricting the seed germination process. Legumes like Albizia or Cassia often exhibit this trait (Baskin & Baskin, 2014).
- **Mechanical Dormancy:** In some species, the seed coat is so rigid that it physically does not allow the embryo to grow.
- **Chemical Dormancy:** Sometimes, inhibitors like abscisic acid (ABA) or phenolic compounds in the seed coverings delay germination (Hilhorst, 2007).

2. Endogenous Dormancy: This originates from the embryo itself and can be either morphological or physiological.

- **Morphological Dormancy:** The embryo is underdeveloped at the time of seed dispersal. Germination is delayed until it matures (Nikolaeva, 1977).
- **Physiological Dormancy:** Despite having a mature embryo, different biochemical reasons within the embryo prevent germination. It often involves hormonal imbalances, exceptionally high ABA levels, and low gibberellic acid (GA) concentrations (Finch-Savage & Leubner-Metzger, 2006).

3. Combinational Dormancy: It is also known as double dormancy. This type involves both physical and physiological constraints. Many wild species, particularly in temperate regions, show this kind of dormancy.

4. Secondary Dormancy: This dormancy develops after seed dispersal when seeds are exposed to prolonged unfavourable conditions. This dormancy can never be overcome once it is induced. It is common in agricultural conditions when the sowing period is not favourable.

Mechanisms behind Seed Dormancy

1. Hormonal Regulation

The hormones are critical to the establishment and maintenance of dormancy. The most important hormone in the promotion of dormancy is abscisic acid (ABA), which inhibits the growth of the embryo. Conversely, gibberellin hormones (GAs) trigger germination by reversing the dormancy that is caused by ABA and provoking enzymes such as amylase that drain the stored food reserves (Finkelstein *et al.*, 2008). The level of these hormones determines whether a seed will remain dormant or begin growing. The temperature, moisture, and other environmental factors determine the influence of hormones on this dormancy.

2. Seed Coat Properties

It is not just that seed coats provide physical protection; their role is also to limit water and gas exchange inside the seeds. In physically dormant seeds, the seed coat remains impermeable until environmental triggers like fire, scarification, or microbial activity alter its structure (Baskin & Baskin, 2014).

Ecological Importance of Dormancy

The strategy can be referred to as dormancy, which contributes to the survival of plants in adverse conditions. It is with this phenomenon that plants have both dormant and non-dormant seeds, where some seeds can grow in favourable seasons, and others can remain dormant and wait. This asynchrony minimizes the likelihood of absolute failure to reproduce in that there would be a sudden increase in environmental stress. Such plants of the desert tend to send out seeds which are dormant as well as non-dormant. This ensures that even if one generation fails due to drought, some seeds remain in the soil to try again when conditions improve (Venable, 2007).

Strategies and Techniques of Breaking Dormancy

From a practical view, dormancy can be an obstacle for crop production and seed germination studies. Over the years, seed scientists have developed various dormancy-breaking methods according to different types of dormancy.

1. Physical Methods: These aim to overcome hard seed coats.

- **Scarification:** In this method, the seed coat is rubbed or nicked with the help of sandpaper or a blade.
- **Thermal Shock:** Hot water is poured over seeds, and then they are allowed to soak in it.

2. Chemical Treatments: Chemical methods are particularly effective for seeds with physiological or chemical dormancy.

- **Soaking in Gibberellic Acid (GA_3):** It promotes germination by natural hormonal changes. GA_3 improves the germination of the seeds and overcomes dormancy.
- **Nitrate or Thiourea Treatments:** These chemicals stimulate respiration and enzyme activity within the seeds (Khan, 1992).

3. Stratification: Cold or warm stratification mimics seasonal changes to break dormancy.

- **Cold Stratification:** Seeds are kept at low temperatures (2–5°C) for several days, weeks, or months, depending upon the seeds and cause of dormancy. This is common in temperate species like apples, cherries, and many grasses.
- **Warm Stratification:** Used for tropical seeds that require warm, moist conditions to initiate germination.

Seed Dormancy in Agriculture

In farming, seed dormancy can be both beneficial and harmful.

Challenges:

- Seeds in dormancy can also lead to unequal germination that can have implications for crop establishment.
- Once delayed sprouting may lower the yields, or in timed sowing, the systems create issues.
- Volunteer crops (seeds that fail to germinate at the time of planting them and germinate during the following year) may turn out to be weeds.

Opportunities:

- Dormancy makes it possible to store off-season without sprouting too soon.
- It increases seed shelf-life and longevity.

- ❖ Dormant varieties are beneficial in direct-seeded rice systems and, as such, decrease the chances of pre-harvest sprouting (Miura *et al.*, 2002).

Through plant breeding, scientists aim to develop crop varieties having controllable dormancy, that is, not too deep to prevent timely germination, yet enough to avoid pre-harvest sprouting. This is especially important for cereals like wheat and barley. Again, new technologies like Artificial Intelligence are bringing significant changes to India's seed sector (Patel, 2025). They can make managing dormancy in seed production much more accurate and efficient.

Recent Advances in Dormancy Research

New advancements in omics technologies, including genomics, transcriptomics, and proteomics, have helped us learn more and more about dormancy at the molecular level. One will be able to pinpoint precisely the gene pathways and protein expression during seed development and dormancy induction. Once again, with the advent of climate change, a new dimension to studies of dormancy has been introduced. Rising global temperatures, unpredictable rainfall, and shifting seasons could disrupt traditional dormancy-germination cycles, especially in wild and endemic plants (Walck *et al.*, 2011). There is an urgent need to re-evaluate dormancy mechanisms under changing environmental scenarios.

Conclusion

Seed dormancy is not only a reduction in germination, but a survival mechanism provided to seeds by nature. Dormancy, be it in deserts, forests, or farms, sees to it that life goes on despite uncertainty. To both farmers and scientists, as well as conservationists, the knowledge of this phenomenon is essential in enhancing crop yields, ecosystem restoration, and genetic maintenance. With time passing and further research, we can get precise in the manipulation of dormancy. This will aid in creating a balance between the lifespan of the seed and its germination at the right time and address the two objectives of food security and environmental sustainability.

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SKILL DEVELOPMENT FOR YOUTHS: A PATHWAY TO EMPLOYMENT AND EMPOWERMENT

Sachin Kumar Sahu[1]*, Praveen Kumar Sahu[2], Ashish Sahu[3], and Santosh[4]

[1]Assistant Professor (Agricultural Extension), Shri Ram College
Muzaffarnagar (UP) – 251001
[2]Associate Professor (Agricultural Economics),
Oriental University- Indore (MP)
[3]Research Scholar, Kerala University of Fisheries and Ocean Studies
Panangad, Cochin- Kerala, Pincode - 682506 (India)
[4]Assistant Professor (Genetics and Plant Breeding), Shri Ram College
Muzaffarnagar (UP) - 251001
*Corresponding Email: sk438198@gmail.com

Introduction

In the rapidly evolving global economy, skill development has emerged as a crucial driver for youth empowerment, employability, and national development. With technological advancements reshaping industries, the demand for a skilled and adaptive workforce has never been greater. Skill development refers to the process of enhancing an individual's capabilities and competencies through education, training, and practical experience (ILO, 2020). For countries like India, where over 65% of the population is below the age of 35, empowering youth with relevant skills is essential for transforming the demographic dividend into a productive economic force (NITI Aayog, 2021).

Concept of Skill Development

Skill development encompasses acquiring technical, vocational, interpersonal, and digital skills that enable individuals to perform efficiently in various occupational settings (UNESCO, 2018). It includes both hard skills, such as computer programming, agricultural mechanization, and manufacturing, and soft skills, such as communication, teamwork, and problem-solving (World Bank, 2019). According to the United Nations Development Programme (UNDP, 2021), effective skill development integrates education, training, and continuous learning to prepare youth for evolving job markets. This approach promotes both employability skills (necessary for securing jobs) and entrepreneurial skills (necessary for self-employment and innovation).

Importance of Skill Development for Youth

1. Enhancing Employability: Skill development equips youth with job-ready competencies, bridging the gap between academic knowledge and industry requirements (OECD, 2020). In many developing economies, employers report skill mismatches where graduates lack the practical skills demanded by industries. Targeted vocational training and apprenticeships help address these challenges by aligning curricula with market trends (ILO, 2021).

2. Economic Growth and Productivity: A skilled youth population contributes directly to national productivity and competitiveness. According to the World Economic Forum (WEF, 2020), a 10% increase in workforce skill levels can raise national output by nearly 4%. Countries such as Germany and South Korea have demonstrated that strong technical education systems and continuous skill upgrading are key to sustained economic success.

3. Entrepreneurship and Innovation: Skill development also nurtures entrepreneurial spirit among youth by providing them with business management, digital, and financial literacy skills. Programs like Start-up India and Atal Innovation Mission in India have promoted youth-led enterprises, contributing to local employment and innovation ecosystems (Ministry of Skill Development and Entrepreneurship [MSDE], 2021).

4. Social Inclusion and Empowerment: For marginalized and rural youth, skill training offers a pathway to social inclusion and financial independence. Empowered youth are better positioned to make informed life choices, contribute to their communities, and participate actively in civic processes (UNDP, 2021).

Major Skill Development Initiatives

1. Global Initiatives: Globally, several initiatives have focused on improving youth skills:

1. The United Nations' Youth2030 Strategy emphasizes lifelong learning and employment-oriented training for sustainable development (UN, 2018).
2. The WorldSkills International movement promotes global standards for vocational excellence (WorldSkills, 2020).
3. The ILO's Skills for Employment Programme supports countries in designing labor-market-responsive training systems (ILO, 2020).

2. Skill Development in India: India has taken significant steps toward creating a skill-based economy through several national programs:

1. Pradhan Mantri Kaushal Vikas Yojana (PMKVY): A flagship scheme under the MSDE offering short-term skill training aligned with industry needs (MSDE, 2021).
2. Skill India Mission (2015): Launched to train over 400 million individuals by 2025 in various sectors (NITI Aayog, 2021).
3. National Apprenticeship Promotion Scheme (NAPS): Encourages on-the-job training by supporting apprenticeships in industries (MSDE, 2022).
4. Deen Dayal Upadhyaya Grameen Kaushalya Yojana (DDU-GKY): Focuses on rural youth and promotes wage employment through skill enhancement (Ministry of Rural Development, 2020).

These initiatives aim to integrate skill training with formal education and ensure employability through industry partnerships.

Challenges in Skill Development: Despite the growing awareness of skill development, several challenges persist:

1. Skill Mismatch: One of the major issues is the mismatch between the skills acquired by youth and those demanded by the job market. Many educational institutions still focus on theoretical knowledge rather than practical training (OECD, 2021).

2. Limited Industry Linkages: The lack of collaboration between training institutions and industries hampers the employability of graduates. Strengthening public–private partnerships is essential for aligning training programs with emerging technologies (World Bank, 2020).

3. Digital Divide: Access to digital learning and skill enhancement platforms remains uneven, particularly in rural and underprivileged regions. Bridging this divide is critical for inclusive development (UNESCO, 2020).

4. Gender Inequality: Women and girls often face barriers to skill training due to social norms, mobility restrictions, and lower access to technology. Inclusive policies are needed to ensure equal participation in the workforce (UN Women, 2020).

Strategies for Effective Skill Development:

1. Integrating Skills with Education: Embedding vocational education within the formal school and higher education system enhances relevance and readiness for work. The National Education Policy (NEP) 2020 in India recommends integrating skill-based learning from secondary education onward (Ministry of Education, 2020).

2. Strengthening Industry-Academia Collaboration: Partnerships between industries and training institutions ensure curriculum relevance, apprenticeships, and hands-on exposure to real work environments (ILO, 2021).

3. Promoting Digital and Green Skills: With automation and sustainability shaping future job markets, promoting digital literacy, data analysis, and green technology skills is vital for youth employability (WEF, 2020).

4. Enhancing Lifelong Learning Opportunities: Establishing continuous learning systems through online platforms, community colleges, and vocational centers ensures that youth remain adaptable to technological and market changes (UNESCO, 2018).

5. Empowering Rural and Marginalized Youth: Targeted training in agriculture, renewable energy, handicrafts, and rural entrepreneurship can create employment opportunities within local communities (FAO, 2021).

The Role of Technology in Skill Development

The advent of digital education platforms, e-learning apps, and virtual training has transformed the skill development landscape. Technologies such as Artificial Intelligence (AI), Virtual Reality (VR), and simulation-based learning make training more interactive and accessible (World Bank, 2021). Initiatives like SWAYAM, eSkill India, and Coursera for Government offer skill-based courses to millions of youth globally, breaking geographical barriers (MSDE, 2022).

Conclusion

Skill development is not just an economic imperative—it is a social and developmental necessity. For youth, acquiring relevant skills ensures employability, entrepreneurship, and empowerment; for nations, it fosters productivity, innovation, and sustainable growth. Strengthening skill ecosystems through education reform, digital inclusion, and policy innovation is essential for preparing youth to meet the challenges of the 21st century. As the global workforce transforms, skill development must evolve continuously, making learning lifelong, inclusive, and adaptive to ensure that today’s youth become tomorrow’s leaders of change.

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SMART FARMING: HOW PRECISION AGRONOMY IS RESHAPING INDIAN AGRICULTURE

Jince Mary M Joy[1*], Triptesh Mondal[2], Pullagura Vijaykumar[3]

[1]Assistant Professor of Agronomy (Contract), On Farm Research Centre,
ORARS, Kerala Agricultural University.
[2]Assistant Professor, Department of Agronomy and Agroforestry,
Centurion University of Technology and Management.
[3]Assistant Professor (Contract), Department of Agronomy,
Polytechnic of Agriculture, Garikapadu, Acharya N.G. Ranga Agricultural University.
*Corresponding Email: jincymundonayil@gmail.com

Introduction: A New Dawn for Indian Farms

India's agricultural landscape is evolving. As the backbone of the economy and the livelihood of millions, farming is entering a new era—one that blends age-old wisdom with cutting-edge technology. Welcome to *smart farming*, where precision agronomy is not just a buzzword, but a powerful force transforming how crops are grown, resources are used, and sustainability is pursued. In this piece, we explore how precision agriculture is taking root in India, its benefits, challenges, and what the future holds.

Precision Agronomy (Smart Farming)

At its core, precision agronomy (or precision agriculture) is about optimizing farming decisions at a highly granular level — tailoring water, fertilizers, pesticides, and other inputs according to the specific needs of small patches of land (rather than treating the entire field uniformly). This approach leans heavily on digital and IoT (Internet of Things) tools, such as:

Precision Farming Matters for India

1. Bridging the Yield Gap

Many Indian farms, especially smallholders, operate far below their yield potential because of over- or under-use of inputs. Precision agronomy helps close this gap by ensuring resources are used exactly where and when needed. According to recent studies, tailored nutrient management and precision irrigation have demonstrably increased productivity.

2. Saving Water

Water scarcity is a pressing concern in India. Precision irrigation using drip systems and soil sensors can significantly reduce water use, while maintaining or increasing output.

3. Cutting Costs & Boosting Profitability

Smart farming doesn't just drive yields; it also optimizes input costs. Less wastage of fertilizer, pesticides, and water translates to more savings for farmers.

4. Environmental Sustainability

By minimizing excessive chemical use and runoff, precision agronomy helps lower pollution. It also contributes to climate resilience by allowing farmers to adapt to erratic rainfall and temperature variations.

5. Policy Momentum & Institutional Support

The Indian government has recognized the potential of smart farming. A ₹6,000 crore scheme is in the pipeline to encourage precision farming using AI, drones, and IoT.

Real Life Applications & Success Stories

Precision agriculture is no longer a futuristic dream in India. it's being implemented, with real benefits, in various regions:

- **Drip Irrigation & Soil Sensors**: In states like Andhra Pradesh and Telangana, IoT-based moisture sensors are used to control drip irrigation systems for horticultural crops, improving water efficiency.
- **Drones for Spraying**: Farmers in Gujarat reportedly use drones to spray fertilizers or pesticides, targeting only the needed areas.
- **GPS-Controlled Machinery**: In Punjab and Haryana, GPS-guided tractors and laser land levellers help sow wheat with millimetre-level precision, leading to better resource use.
- **State-level Innovations**: For instance, a 28-year-old farmer from Ganjam (Odisha) uses a 15-kg capacity drone to spray liquid fertilizer, significantly cutting labor, time, and cost.
- **Autonomous Tractors**: Punjab Agricultural University demonstrated a system where tractors with AI and satellite-guidance can auto-steer potentially reducing fuel use and drudgery.
- **Robotic Pest Control**: IIT Kharagpur has developed a robot that can detect disease or pests and apply pesticides precisely.

Challenges & Roadblocks

Despite its promise, smart farming in India faces several hurdles:

Fragmented Land Holdings

Many Indian farmers have small, scattered plots. This fragmentation makes it economically challenging to deploy high-cost precision tools.

High Initial Investment

Buying sensors, drones, and GPS-technology requires capital, which can be prohibitive, especially for smallholders.

Digital Literacy Gap

Not all farmers are familiar with using digital tools or interpreting the data from them.

Infrastructure Issues

Poor internet connectivity, intermittent power, and lack of local technical support limit real-time data collection and action.

Policy & Regulatory Barriers While there's government support, issues remain around standardization, data ownership, and clear regulation of drone usage.

Maintenance & Training Precision tools need maintenance. Also, extension services currently are often not equipped to guide farmers on data-driven farming.

Vision for the Future: What Smart Farming Could Mean for Indian Agriculture

As smart farming scales, it has the potential to reshape Indian agriculture in profound ways:

- **Decarbonizing Agriculture**: By optimizing input use, precision agronomy can reduce emissions and environmental footprint.
- **Resilient Farming Systems**: With climate change driving unpredictability, smart farming offers tools for resilience like early-warning systems for pests or stress.
- **Inclusive Growth**: Through shared models (FPOs, service providers), even smallholder farmers can access high-tech solutions.

- **Sustainable Food Systems**: Higher, more consistent yields can contribute to food security, while minimizing resource depletion.
- **Data-Driven Policy**: Aggregated farm-level data can help policymakers identify trends, target interventions, and design more effective agricultural programs.

Conclusion

Smart farming is not just about gadgets it's a paradigm shift. Precision agronomy empowers Indian farmers to grow more with less, conserve precious resources, and build resilience in a changing climate. While challenges remain such as cost, digital access, and infrastructure—the momentum is undeniable. Government initiatives, institutional support, and the entrepreneurial energy of agritech startups are converging to make this vision a reality.

If adopted widely and thoughtfully, precision agronomy could herald a future where Indian agriculture is not just productive, but sustainable, equitable, and innovation-driven. In that future, every farm whether large or small has the potential to be a *smart farm*.

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SMART FARMING: IOT-ENABLED SENSORS AND DRONES FOR PRECISION AGRICULTURE

Anerao Kishor K[1*], Deshpande H. W[2] and Pratyush Kumari Rath[3]

[1]Ph.D. Research Scholar, Department of Food Microbiology and Safety,
CFT, VNMKV, Parbhani.
[2]Professor and Head Department of Food Microbiology and Safety,
CFT, VNMKV, Parbhani
[3]Ph.D. Research Scholar, Department of Economics,
COA, VNMKV, Parbhani
*Corresponding Email: kishoranerao135101@gmail.com

Abstract

This review synthesizes research on "Smart Farming: IoT-enabled sensors and drones for precision agriculture, focusing on technological aspects, impacts and benefits, regional applications, and challenges" to address gaps in sustainable agricultural technology adoption amid global resource and climate pressures. The review aimed to evaluate current IoT and drone technologies, benchmark smart farming systems, analyze impacts on productivity and sustainability, assess regional adoption patterns, and identify implementation challenges. A systematic analysis of diverse studies employing case reports, technological assessments, and regional evaluations was conducted, emphasizing innovations such as AI-integrated drones, edge computing, and Internet of Drones frameworks. Findings reveal significant yield improvements and resource efficiency gains driven by advanced sensor and machine learning applications, alongside notable environmental benefits including water conservation and reduced chemical use. Regional adoption varies widely, influenced by infrastructural, socio-economic, and policy factors, with developing regions facing pronounced barriers related to cost, connectivity, and digital literacy. Persistent challenges include data privacy, regulatory constraints, and scalability limitations, while integration of AIoT systems shows promise for enhanced automation and decision support. Overall, the evidence underscores the transformative potential of IoT-enabled smart farming but highlights the need for inclusive, context-specific strategies and robust policy frameworks to overcome technological and socio-economic obstacles in order to advance precision agriculture sustainability globally.

Key words: Smart farming, Internet of Things (IoT), precision agriculture, drones, artificial intelligence (AI), machine learning, sustainable agriculture, resource optimization, agricultural automation, data-driven farming, AIoT, climate-smart agriculture

Introduction

Research on smart farming, particularly IoT-enabled sensors and drones for precision agriculture, has emerged as a critical area of inquiry due to its potential to address global challenges such as food security, climate change and sustainable resource management (Guebsi *et al.*, 2024) (Kumar *et al.*, 2024). The evolution of precision agriculture has been marked by the integration of advanced technologies, from early GPS-guided equipment in the 1980s and 1990s to contemporary IoT and AI-driven systems that enable real-time monitoring and data-driven decision-making (Anand *et al.*, 2023). This technological progression has significant social and practical implications, including increased crop yields, optimized resource use and reduced environmental impact, which are vital for feeding a growing global population projected to reach 9.7 billion by 2050 (Marinello *et al*., 2023).

For instance, IoT-based irrigation systems have demonstrated water use efficiency improvements of up to 20%, highlighting the practical benefits of these innovations (Arularasan *et al*., 2024) (Chithra *et al*., 2024).

Despite these advances, specific challenges persist in the adoption and implementation of smart farming technologies. Key problems include high initial costs, limited digital infrastructure in rural areas, data privacy concerns and the need for farmer training (Guamán-Rivera, 2023) (Bhatt, n.d.) (E *et al*., 2024). Moreover, there is a knowledge gap regarding the integration of IoT sensors and drones across diverse regional contexts and crop types, as well as the socio-economic and regulatory barriers affecting technology acceptance (Assimakopoulos *et al*., 2024) (Singh *et al*., 2022). Competing perspectives exist on the balance between technological sophistication and accessibility, with some advocating for high-tech solutions and others emphasizing cost-effective, scalable approaches (Deepasree *et al*., 2024). Failure to address these gaps could hinder the widespread adoption of precision agriculture, limiting its potential to enhance sustainability and productivity (Modjo *et al*., 2024).

Comparative analysis of key research questions

The comparative analysis addresses key research questions by benchmarking technological innovations, assessing productivity impacts, examining regional adoption patterns, identifying implementation challenges, and evaluating sustainability outcomes as follows.

Technological Innovation

Recent studies have demonstrated that advanced integration of IoT sensors, drones, AI, and machine learning, with innovations such as multispectral sensors, autonomous UAVs, and edge computing frameworks enhancing precision agriculture capabilities (Guebsi *et al*., 2024) (Hayajneh *et al*., 2023). Emergence of Internet of Drones (IoD) and AIoT paradigms enables the autonomous drone control and intelligent decision-making, which represens cutting-edge technological progress (Adli *et al*., 2023). Innovations also include the use of TinyML for on-edge processing, transfer learning for soil moisture prediction and integration of blockchain and cloud computing for data security and management (Hayajneh *et al*., 2023).

Impact on Productivity

Use of IoT demonstrated the improvements in crop yield, with increases ranging from 15% to 30%, alongside enhanced resource use efficiency such as water and fertilizer savings (Ranjan *et al*., 2025). AI and machine learning applications contribute to precise irrigation, disease detection and yield prediction, leading to operational cost reductions and optimized input application (Polwaththa *et al*., 2024) (Levin, 2024). Some studies emphasize personalized crop management and risk mitigation through predictive analytics, further boosting productivity and reducing losses (Mahmood *et al*., 2024) (Akintuyi, 2024).

Regional Adoption Rate

Research spans global contexts, with notable focus on India, Africa, arid regions, and developed countries, reflecting diverse socio-economic and climatic conditions influencing adoption (Verma, 2023). Several studies underscore challenges in developing countries related to infrastructure, digital literacy, and financial resources, limiting widespread technology uptake (Guamán-Rivera, 2023) Government initiatives and policy support are identified as critical enablers for regional adoption, especially in emerging economies (Assimakopoulos *et al*., 2024) (Debangshi *et al*., 2023).

Challenge Identification and Resolution

Common barriers include high initial costs, data privacy and security concerns, connectivity issues, and lack of technical expertise among farmers (Ranjan *et al*., 2025) (Kumar *et al*., 2024). Regulatory challenges, particularly for drone operations such as BVLOS flights, and socio-economic factors like farmer acceptance and training needs are frequently reported (Singh *et al*., 2022). Proposed solutions involve policy frameworks, collaborative stakeholder engagement, affordable technology development, and capacity-building programs (Anand *et al*., 2023) (Adli *et al*., 2023).

Sustainability Outcomes

Many studies revealed measurable environmental benefits including water conservation, reduced chemical usage, and lower carbon footprints through optimized resource management (Getahun *et al*., 2024) (Sachan & Singh, 2024). AI and IoT-enabled systems contribute to sustainable farming by minimizing waste, enhancing soil health, and supporting biodiversity (Khadka & Kumar, 2024) (Obaid *et al*., n.d.). Some research highlights the role of smart agriculture in climate change resilience and promoting eco-friendly practices (Hashir *et al*., 2024) (Hoque, 2025) (Gupta, 2025).

Study	Technological Innovation	Impact on Productivity	Regional Adoption Rate	Challenge Identification	Sustainability Outcomes
(Guebsi *et al*., 2024)	Advanced drones with multispectral sensors and AI integration	Improved yield estimation and irrigation management	Case studies across diverse crops globally	Regulatory and economic barriers, BVLOS flight restrictions	Enhanced resource use, early disease detection
(Arularasan *et al*., 2024)	IoT-connected drones with machine learning for irrigation	20% increase in crop yield and water use efficiency	Focus on water-scarce regions, especially arid zones	Technical complexity and cost of deployment	Significant water conservation and operational cost reduction
(Ranjan *et al*., 2025)	AI-driven drones and sensors for eco-friendly farming	Increased crop yields and reduced input costs	Global applications with emphasis on sustainability	High initial costs and data privacy concerns	Lower environmental footprint and resource optimization
(Chithra *et al*., 2024)	Integrated AI, drone, and ground sensor irrigation system	Enhanced water efficiency and crop productivity	Targeted at arid regions with water scarcity	Infrastructure and skilled labor shortages	Reduced water waste and climate change resilience
(Getahun *et al*., 2024)	Remote sensing, GPS, VRT, and IoT	Boosted crop yields and	Global coverage with	Adoption barriers in	Reduced chemical use

Study	Technological Innovation	Impact on Productivity	Regional Adoption Rate	Challenge Identification	Sustainability Outcomes
	for precision agriculture	profitability	emphasis on environmental sustainability	developing countries	and greenhouse gas emissions
(Maravarman *et al*., 2024)	IoT sensors, GPS, and automation for resource optimization	Improved operational efficiency and resource use	Diverse regional applications with regulatory considerations	Data privacy, security, and ethical challenges	Efficient water and fertilizer management
(Kumar *et al*., 2024)	Comprehensive IoT applications including drones and sensors	Increased productivity and reduced resource wastage	Global scope with focus on connectivity and cost issues	Connectivity, data security, and scaling challenges	Enhanced sustainability through optimized inputs
(Assimakopoulos *et al*., 2024)	IoT synergy with weather forecasting and robotics	Real-time crop monitoring and yield prediction	Worldwide adoption with government support	Learning curve and installation costs	Sustainable practices and improved food security

Strengths and Weaknesses

The integration of AI and machine learning with IoT and drone technologies emerges as a critical enabler for real-time decision-making and automation, yet concerns about data privacy, infrastructure readiness and regulatory frameworks remain underexplored.

Aspect	Strengths	Weaknesses	References
Technological Advancements	Smart farming has seen major tech leaps—like drones with multispectral imaging, AI for disease detection, and real-time monitoring. Innovations like drone swarms, edge AI (TinyML), and integrated AIoT systems are making farm-level operations more efficient.	Despite progress, many tools still struggle in tough field conditions due to limited durability, power issues, and sensor accuracy. Integrating different systems remains complex, slowing real-world use.	Hayajneh *et al*., 2023; Guebsi *et al*., 2024
Impact on Productivity and Sustainability	Precision technologies are boosting crop yields, saving water and fertilizers, and lowering environmental impact. Tools like AI-based prediction and smart irrigation have shown real gains in efficiency and plant health.	Most studies focus on small-scale pilots and short-term gains, with limited data on long-term or broad regional impacts. Costs and benefits, especially for small farmers, are often not fully assessed.	Arularasan *et al*., 2024; Hoque, 2025
Regional Applicatio	Localized studies—especially from South and Southeast Asia—	There’s a lack of broader comparisons across different	Verma, 2023; Kumar *et al*.,

Aspect	Strengths	Weaknesses	References
ns and Contextualization	show how adapting technology to local conditions improves adoption and impact. These efforts reflect socio-economic and infrastructural realities.	climates and farming systems. Many studies center on better-funded regions, overlooking marginalized or under-resourced communities.	2024
Challenges and Barriers to Adoption	Common hurdles include high setup costs, technical complexity, privacy concerns, and unclear regulations. Farmer awareness, training, and openness to tech are key social factors.	While challenges are well known, practical solutions or policies are often missing. The mix of technical, financial, and social issues needs deeper study. Topics like job loss and data ownership are also not widely discussed.	Assimakopoulos *et al*., 2024; Polwaththa *et al*., 2024

Conclusion

Smart farming technologies, especially IoT-enabled sensors and drones, are revolutionizing precision agriculture by improving yield, optimizing resource use and supporting environmental sustainability. Innovations like AI integration, edge computing and autonomous systems show high potential but face practical limitations such as high costs, data privacy issues and lack of rural infrastructure. While localized success stories exist, broader adoption is hindered by socio-economic and policy gaps. To fully explore the promise of smart farming, inclusive strategies, affordable solutions and strong policy frameworks are essential for scalable and equitable implementation.

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SMART WAREHOUSING AND INVENTORY AUTOMATION IN FOOD SUPPLY CHAINS

Mehazabeen. A[1], J Tamal Atab[2*] and Y. Shelton Peter[3]

Assistant Professor, Department of Agri Business Management,
SOM, Centurion University of Technology and Management, Odisha - 761211.
Ph.D. Research Scholar, School of Development Studies,
Tata Institute of Social Sciences, Deonar, Mumbai, Maharashtra – 400088.
Assistant Professor & Head, Department of Agricultural Economics,
Sri Krishna Devaraya College of Agricultural Sciences,
Anantapuramu, Andhra Pradesh-515001
*Corresponding Email: jtamalatab15@gmail.com

Introduction

In India, nearly 30–40% of fruits and vegetables are lost before they reach consumers, mainly due to gaps in storage, handling, and transportation. These post-harvest losses not only erode farmers' incomes but also push up food prices and threaten national food security. As the country's agri-sector moves toward modernization, smart warehousing and inventory automation driven by Internet of Things (IoT) technologies are emerging as transformative tools to make food logistics more efficient, transparent, and sustainable.

From Traditional to Smart Warehouses

For decades, India's food warehouses operated with limited technology, manual record keeping, static temperature control, and delayed decision-making. These traditional systems often led to inefficiencies, especially when handling perishable commodities that require constant monitoring.

The new era of smart warehousing is transforming this landscape by integrating IoT-enabled systems that bring precision and control into every operation. Smart sensors, RFID tags, and automated monitoring devices now track temperature, humidity, and stock levels in real time. If the temperature inside a cold storage rises beyond the optimal range, an alert is instantly sent to warehouse managers, allowing immediate corrective action.

Beyond monitoring, automation ensures predictive management, and cooling systems can self-adjust based on produce type and ambient conditions, reducing energy costs while maintaining freshness. For crops like onions, tomatoes, or mangoes, this real-time responsiveness can mean the difference between a profitable consignment and a wasted one. By moving from reactive maintenance to proactive control, smart warehouses help India's agri-value chains minimize losses, improve storage efficiency, and ensure better quality delivery to both domestic and export markets.

Inventory Automation: Precision Meets Efficiency

Managing inventory in traditional warehouses often relied on manual counting, paperwork, and human judgment methods that are slow, error-prone, and poorly suited to handling perishable goods. Today, inventory automation powered by digital tools is transforming how agri-warehouses operate. Technologies such as RFID (Radio Frequency Identification), barcoding, and automated data capture systems allow real-time tracking of every product entering or leaving a warehouse. These systems feed data directly into a Warehouse Management System (WMS), which updates inventory levels automatically, flags slow-moving or ageing stock, and even predicts future demand based on consumption patterns. For food processors and exporters, such automation supports dynamic stock rotation, ensuring that perishable items follow the "First Expire, First Out" (FEFO) principle. This not only reduces spoilage but also strengthens supply chain reliability and traceability.

The integration of artificial intelligence (AI) and data analytics further enhances decision-making, allowing managers to optimize storage layouts, forecast sales, and reduce waste. In short, inventory automation ensures precision, speed, and sustainability, enabling the food supply chain to operate more like a synchronized ecosystem than a series of disconnected steps.

IoT in Logistics: From Farm Gate to Fork

In a country as vast and diverse as India, moving food efficiently from farms to consumers is a complex challenge. Every stage of collection, storage, transport, and retail presents opportunities for both value creation and loss. This is where the Internet of Things (IoT) is redefining agricultural logistics, connecting each link in the chain through a network of smart devices and sensors. IoT-enabled cold-chain trucks, for instance, are equipped with temperature, humidity, and GPS sensors that transmit data continuously to logistics control centres. If the temperature inside a vehicle rises beyond the permissible limit or if there's an unexpected route delay, the system sends an instant alert to managers, allowing immediate action to prevent spoilage.

These technologies also enable route optimization, reducing fuel consumption, travel time, and greenhouse gas emissions. When combined with cloud-based platforms, logistics operators can track produce in real time, providing both farmers and buyers with greater visibility and confidence in product quality. For exports of sensitive commodities such as mangoes, dairy products, seafood, and floriculture items, IoT-powered logistics ensure that temperature and quality standards are maintained throughout transit, meeting stringent global market requirements.

Reducing Post-Harvest Losses: The Digital Dividend

One of the most significant benefits of smart warehousing and IoT-enabled logistics is their direct impact on reducing post-harvest losses, a persistent challenge in India's agri-food system. By enabling real-time monitoring, automated control, and data-driven decision-making, these technologies minimize spoilage, ensure timely handling, and improve overall efficiency. IoT sensors help maintain ideal environmental conditions, temperature, humidity, and gas composition within storage and transport units. Predictive analytics can forecast when equipment maintenance is needed, preventing unexpected failures that lead to product loss. Similarly, digital alerts allow quick responses to power outages or temperature fluctuations in cold storage, ensuring that perishables remain safe and market-ready.

According to pilot projects supported by agencies like NABARD, APEDA, and the Ministry of Agriculture, IoT-based cold-chain solutions have reduced spoilage rates by 20–25% in select horticultural crops. For Farmer-Producer Organizations (FPOs) and agri-startups, these technologies translate into higher profits, reduced wastage, and better market linkages. Beyond the economics, the benefits extend to food security and sustainability. By preventing food loss, smart systems help conserve natural resources water, land, and energy that go into producing every kilogram of food. Thus, digital innovation is not just improving efficiency; it is also strengthening resilience and sustainability across India's food supply networks.

The Road Ahead and Conclusion

India's agricultural logistics are undergoing a quiet revolution. With government initiatives such as the PM Gati Shakti Mission, the Agriculture Infrastructure Fund (AIF), and the Digital India program, the foundation for a technology-driven supply chain is already being laid. However, to fully realise the potential of smart warehousing and IoT-based inventory systems, a few key challenges must be addressed, namely, cost, connectivity, and capacity building. For smallholder farmers and rural cooperatives, the initial investment in IoT infrastructure can be prohibitive. This is where public–private partnerships and agri-tech startups play a crucial role, offering low-cost sensor technologies, cloud-based data platforms, and mobile-friendly applications tailored for India's rural ecosystem. Similarly, training and upskilling warehouse staff and FPO members in digital tools will ensure smooth adoption and long-term sustainability.

Conclusion

Emerging technologies such as blockchain and artificial intelligence promise to take this transformation even further, enabling end-to-end traceability, smarter demand forecasting, and transparent pricing for farmers and consumers alike. In the bigger picture, smart warehousing and inventory automation are not just technological upgrades; they represent a shift toward sustainability, efficiency, and equity in the food supply chain. By connecting farmers, processors, and consumers through data and intelligent systems, IoT is helping to reduce post-harvest losses, boost farmer incomes, and strengthen food security.

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SPECIALTY AND UNDERUTILIZED CROPS: THE NEW FRONTIER IN HORTICULTURE

Shivaraj Kumar Verma

Assistant Professor, Department of Horticulture,
Udai Pratap (Autonomous) College, Varanasi
Corresponding Email: shivraj.vns@gmail.com

Introduction: A Silent Revolution Rooted in Forgotten Fields

Across India's diverse landscapes from the dry lands of Rajasthan to the humid tropics of Kerala a silent horticultural revolution is unfolding. Farmers, researchers, and Agri-startups are rediscovering crops that have long lived in the shadows of mainstream agriculture. These are specialty crops and underutilized **crops** rich in nutrition, resilient in harsh climates, and brimming with commercial potential.

As climate stress increases, consumer preferences shift toward health foods, and global markets demand unique flavours, these crops are emerging as the new frontier of modern horticulture. Once regarded as "minor crops," they are now stepping into the spotlight with the promise of sustainable income, climate resilience, and nutritional security.

What Are Specialty and Underutilized Crops?

Specialty Crops

These include high-value, niche-market crops grown for premium quality, unique flavour, medicinal properties, or export potential.

Examples:

- Berries (blueberry, raspberry, strawberry)
- Exotic vegetables (broccoli, lettuce, asparagus, zucchini)
- Spices and herbs (oregano, thyme, rosemary)
- Specialty fruits (dragon fruit, passion fruit, kiwifruit)
- Microgreens and salad crops

Underutilized or Neglected Crops

These are traditional crops that have strong climate resilience, high nutrition, and cultural value but remain underexplored commercially.

Examples:

- Millets (foxtail, little millet, kodo)
- Jackfruit
- Bael, jamun, tamarind
- Drumstick (moringa)
- Custard apple (sitaphal)
- Breadfruit
- Winged bean, rice bean

Both categories are now redefining the future of horticulture.

Renewed Focus: The Changing Landscape of Demand and Climate

1. Climate Resilience

Underutilized crops like bael, drumstick, jamun, millets, and custard apple thrive in drought, heat, poor soils, and low rainfall.

As global warming intensifies, these hardy species protect farmers from climate risks.

2. Nutritional Powerhouses

Many specialty and underutilized crops possess:

- High dietary fibre
- Powerful antioxidants
- Vitamins and minerals
- Therapeutic value

This aligns perfectly with India's rising demand for functional foods and immunity-boosting diets.

3. High Market Value

Exotic vegetables, berries, and culinary herbs command premium prices in:

- hotels & restaurants
- supermarkets
- export markets
- online fresh-food platforms

A small area under these crops can generate impressive income for small and marginal farmers.

4. Government Push

Policies promoting:

- Millets as "nutri-cereals"
- Horticulture diversification under MIDH
- Tribal crop processing (TRIFED)
- ICAR research on climate-resilient species

Top Specialty and Underutilized Crops Redefining Horticulture

1. Dragon Fruit (Pitaya): The New Star of Indian Orchards

Once rare, dragon fruit is now cultivated widely in Gujarat, Maharashtra, Karnataka, Telangana, and Odisha.

Its advantages:

- drought tolerance
- high profitability (₹6–8 lakh/acre)
- low maintenance
- strong demand in urban markets

2. Berries: The Health Superstars

Blueberries, raspberries, blackberries, and strawberries are gaining fast popularity.

- Strawberries thrive in Maharashtra, Himachal Pradesh, and Meghalaya.
- Blueberries are emerging through protected cultivation and hydroponics.

3. Exotic Vegetables: From Gourmet to Mainstream

Crops like:

- broccoli
- cherry tomato
- lettuce
- zucchini
- asparagus
- coloured capsicum

4. Millets & Pseudo-Cereals: Ancient Crops, Modern Comeback

Millets such as:

- foxtail
- barnyard
- kodo
- proso

along with quinoa and amaranthus, are being promoted as **superfoods**.

Their:

- short duration
- low input needs
- market demand
- …make them ideal for climate-smart farming.

5. Jackfruit and Bael: From "Village Trees" to Value-Chain Heroes

Jackfruit, once seen as a rural staple, is now processed into:

- jackfruit flour
- chips
- nuggets
- pulp
- frozen cubes

Bael is gaining demand in:

- health products
- juices
- nutraceuticals

Both crops tolerate heat and drought exceptionally well.

6. Moringa (Drumstick): The Miracle Tree

Moringa is rich in:

- Vitamin C
- iron
- calcium
- antioxidants

Products such as moringa powder, capsules, and tea are booming globally. It grows easily even in dry zones, offering steady income with minimal investment.

7. Medicinal and Aromatic Plants

The AYUSH boom has increased demand for:

- ashwagandha
- safed musli
- vetiver
- lemongrass
- rosemary
- oregano

These crops need low water, are pest-resistant, and fetch strong prices for processing industries.

8. Custard Apple (Sitaphal): A Dryland Delight

This hardy fruit tree grows in poor soils and extreme temperatures. New hybrids like 'Arkaharitha' and 'Balanagar' offer:

- higher yield
- bigger fruit
- longer shelf life

Custard apple pulp has a booming demand in ice creams and beverages.

Conclusion

Specialty and underutilized crops are more than a trend — they represent the next phase of horticulture diversification in India. By combining traditional wisdom with modern science, these crops provide:

- climate resilience
- higher profitability
- nutritional richness
- reduced input costs
- new markets
- sustainable farming systems

In a world grappling with climate change, soil degradation, and changing consumer habits, the future of horticulture will belong to crops that are resilient, nutritious, and niche. The next green revolution will not come from expanding land—it will come from expanding diversity.

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THE HIDDEN DANGER IN COOKING OIL: UNDERSTANDING THE ADULTERATION OF PALM OIL

Oluwatoyin Zaka, David Ahmed Adamu*, Deborah Olabode

Research Outreach Department, Nigerian Stored Products Research Institute
*Corresponding Email: adamuad@nspri.gov.ng

Abstract

Palm oil is a fat rich source, essential commodity of great economic importance in Nigeria food system. It remains widely used in both traditional and food industry in the generations of human history. It is high in antioxidants, vitamin K, E and A which contains beneficial carotenoid. All these enhance healthy skin, vision and immune system. *Elaeis guineesis* produces high quantity of oil over small areas of land all year round with steady income which make it attractive to grower. However, the adulteration of palm oil is now a major food safety concern. This article examines the prevalence, causes and implication of palm oil adulteration. Many engagers indulge in a practice of adding harmful substances such as dye, kerosene, cheaper vegetable oil or reused oil with endless of others to palm oil. This is to increase their profit margin at the expense of the consumers, not minding the risks such as nutritional degradation, organ damage and cancerous diseases posed. This review also includes socioeconomic impact of this practice on producers and national trade reputation. Simple detection methods of the adulterated commodity were outlined, while strong calls were made to regulatory enforcement, quality control and consumer education to take proper and adequate measure to ensure the purity of palm oil. These are steps which are crucial in safeguarding public health, restoration of market trust and sustainability of the palm oil value.

Keywords: Losses, Palm-Oil, Nutrition, Adulteration, Health

Introduction

Palm oil, fondly called “the red gold of Africa,” is one of the most consumed edible oils in Nigeria and many parts of the world. It is rich in vitamins A and E, and serves as a key ingredient in cooking, food processing, and cosmetics. However, growing concerns have emerged about the adulteration of palm oil, a practice where unscrupulous vendors mix genuine palm oil with harmful substances to improve color, volume, or profit margins.

Palm oil adulteration involves the deliberate addition of foreign substances such as artificial dyes (like Sudan III or IV), used cooking oil, or other cheaper vegetable oils. These additives may enhance the oil’s color or texture, deceiving consumers into thinking they are buying high-quality products (Okechalu et al., 2011). Common additives include Sudan dyes, recycled oil, and cheaper vegetable oils, all of which degrade quality and introduce toxic compounds (Onyeonagu et al., 2018). Studies show that adulterated palm oil can cause organ damage, oxidative stress, and even cancer (Okechalu et al., 2011). This act not only reduces nutritional value but also poses serious health risks to consumers. Despite these dangers, local markets still sell such commodity.

Nigeria being one of the top palm oil producer established agencies such as the National Agency for Food and Drug Administration and Control (NAFDAC) and the Standards Organisation of Nigeria (SON) to regulate food quality. However, limited resources, insufficient laboratory capacity, poor coordination, and corruption hinder their effectiveness (FAO, 2020). Millions of potential export earnings are lost due to questionable quality of Nigeria palm oil (FAO, 2020). Many small-scale processors operate informally, outside official oversight, while regulatory inspections are often reactive rather than preventive. The absence of traceability systems also makes it difficult to identify the source of adulterated products once they reach consumers.

Potential risks of palm oil Adulteration

Adulteration of palm oil has severe health consequences. Sudan dyes are carcinogenic, potentially leading to liver and kidney damage, and long-term exposure may increase cancer risk (Onyeonagu et al., 2018). Recycled or oxidized oils contain peroxides that can cause digestive disorders, heart diseases, and cellular damage. Over time, these contaminants accumulate in body tissues, impairing normal metabolic function and weakening immunity. Beyond health, adulteration undermines consumer trust, damages export potential, and discourages genuine producers.


Precautional Measures

Consumers can take these simple steps to determine the quality of palm oil they are about to purchase:

- Observe color: genuine palm oil is deep reddish-orange, not overly bright or fluorescent.
- Smell and texture: pure oil has a natural nutty aroma and thick texture, not watery or chemical-smelling.
- Use basic tests: when palm oil is refrigerated, adulterated samples often separate into layers.

Producers should embrace Good Manufacturing Practices (GMP), while government agencies such as NAFDAC and SON must intensify quality monitoring and public sensitization.

Conclusion

Palm oil adulteration threatens both food safety and public health. The purity requires adherence to quality standards which should be collective effort from all the stakeholders. The “red gold” should nourish, not harm, those who consume it. Stricter enforcement against palm oil adulteration should therefore not be a mere regulatory demand, but rather a public health necessity and an economic safeguard. With all stakeholders working together as an entity, every drop of palm oil sold is ensured safe, pure and beneficial. Hence, Nigerian reputation on palm oil market can be restored to pave way for competitiveness in both regional and international trade.

Recommendation

1. NAFDAC and SON should increase routine sampling and testing at all levels of distribution through regular market surveillance.

2. Implementation of fines and prosecution for offenders to discourage adulteration by the Legal arm of Government.
3. Equip laboratories and train inspectors in modern analytical techniques like FTIR spectroscopy, chromatography, and chemometric tools for easy detection of adulteration of oil.
4. Encourage collaboration with producer associations and research institutions for self-regulation.
5. Use media campaigns to inform the public on identifying and reporting adulterated products.

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SPOILAGE IN CANNED SEAFOOD PRODUCTS

Nidhi Dhansukhbhai Patel*, Kishan Kishorchandra Kalaria,
Bhavika Tandel, Vijay Kumar, Katira Naresh

Assistant Professor, College of Fisheries Science, Kamdhenu University, Navsari
*Corresponding Email: nidhi25.np@gmail.com

Abstract

The article focuses the complex factors influencing spoilage in canned foods. Starting from Nicolas Appert's pioneering technique of sealing food in heated jars, the article explains why preservation is crucial for food safety, waste reduction, and year-round supply stability. Most spoilage microorganisms produce gases that cause visible swelling in cans, while some produce acids without gas, making spoilage detection more difficult. The causes of spoilage, including microbial growth before processing, contamination from faulty seals after processing, survival of heat-resistant bacteria, and growth of thermophilic microbes at high storage temperatures. Chemical and physical changes during processing and storage, such as nutrient loss, Maillard browning, and off-odors are also discussed. The types of spoilage caused by different bacteria, yeasts, and molds, including those that uniquely affect marine products like fish, shrimp and crab is also explained. By understanding these scientific spoilage mechanisms, food producers can adopt better processing, packaging, and storage practices to ensure canned food quality and consumer safety.

Keywords: *Fish, Canning, Preservation, Spoilage*

Introduction

Nicolas Appert, a French chef and confectioner, created the first successful commercial method for preventing food spoilage in response to a challenge from the French government seeking a way to preserve food for the military. After extensive trials, Appert perfected a technique in which food was sealed in jars and cooked at high temperatures, earning him a 12,000-franc prize in 1810. He described his preservation process in his 1811 book, *"L'Art De Conserver, Pendant Plusiers Années, Toutes les Substances Animales et Végétales"* ("The Art of Preserving All Kinds of Animal and Vegetable Substances for Several Years"). Appert was also known as the "Father of Canning." (Evancho *et al*., 2010).

Why is there a need to Preserve Food?

- Prevents spoilage and foodborne illness
- Reduces waste
- Ensures year-round food availability
- Supports food security and economic stability

All spoilage results in economic losses, but not all pose health hazards. Since distinguishing between pathogenic and non-pathogenic spoilage can require specialized testing, all spoiled products should be treated cautiously to avoid consumer exposure. People should be advised never to consume food from swollen cans or visibly spoiled products, even if the container appears normal (Peterson, 2024).

Spoilage in heat-processed foods can occur due to:

1. Microbial growth to high numbers before processing (incipient spoilage).

2. Entry of microorganisms after processing due to faulty seals or seams (post-process or leakage spoilage).
3. Survival of microorganisms from inadequate heating (inadequate thermal processing).
4. Growth of heat-loving microorganisms during high-temperature storage.
5. Growth of acid-tolerant, spore-forming microorganisms in products with pH ≤ 4.6.
6. Non-microbial factors that degrade food quality.

Changes taking place during processing

During the processing of canned foods, several physical and chemical changes occur that can be grouped into desirable and undesirable categories. These changes may also be classified as those responsible for spoilage and those that are not.

Desirable Changes

- Enzyme inactivation: Heat treatment during processing destroys enzymes that could otherwise cause food deterioration.
- Elimination of microorganisms: The sterilization process kills harmful and spoilage-causing microbes.
- Salt penetration: In canned fish and similar products, salt absorption enhances preservation and flavor.
- Softening of bones and tissues: Heat processing softens bones, fins, and scales, making them edible and improving the uniformity of taste and aroma throughout the product (as in curry-style canned foods).
- Formation of color and aroma: Controlled Maillard reactions during heating develop characteristic color and pleasant aroma.

Undesirable Changes

- Nutrient loss: Certain amino acids and vitamins may be destroyed by the heat used in processing.
- Oxidation of fats: Fatty components can oxidize, leading to rancidity and off-flavors.

Spoilage in Canned Foods

Although bulged cans are usually discarded, the contents inside may not always be inedible. Not all swelling is due to microbial spoilage. Some bacteria, such as *Bacillus stearothermophilus*, spoil food without gas production, resulting in normal-looking cans with flat ends. In such cases, the food inside has increased acidity (low pH) and a sour taste, a condition known as flat sour spoilage.

Types of Bulged (Swollen) Cans

Bulged cans are generally divided into four categories:

- **Flipper**: The internal pressure is nearly equal to or slightly higher than the atmospheric pressure, just enough to make the end of the can flip out when tapped. The end returns to its normal shape when pressed. Causes include insufficient exhausting, early hydrogen formation, early microbial activity, or spoilage before processing.
- **Springer**: The inside pressure is higher than in a flipper. One end stays permanently convex, and when that end is pressed, the opposite end bulges out. The causes are similar to those of a flipper.
- **Soft swell**: Both ends of the can are permanently bulged but can be slightly depressed with finger pressure; they regain their shape once pressure is released.

- **Hard swell**: Both ends remain permanently convex and cannot be pressed in. This is due to a high buildup of gases, excessive hydrogen generation, or advanced microbial spoilage
- Bombed cans: In some severe cases, cans may rupture or leak due to extreme internal pressure.

Causes of spoilage in canned foods

For canned foods to be considered free from spoilage, both the container's condition and the quality of its contents must be intact. Spoilage can occur due to several factors, broadly classified into physical, chemical, and microbial causes.

Physical Causes

Cans may suffer physical damage during handling, such as when they are lifted, transported, loaded into baskets for heat processing, or packed into boxes without proper care. Minor dents generally do not affect the contents, but dents located on or near the double seam can loosen it, leading to leakage.

Sudden changes in pressure during retorting can cause *panelling* (collapse of can walls). Overpacking is another issue; without sufficient space for the contents to expand during heat treatment, cans may develop flipper or springer-type bulging. Overpacked cans may also receive inadequate heat processing, allowing surviving bacteria to multiply inside and cause spoilage.

Additionally, manufacturing defects like weak seams can make cans more prone to leakage-related spoilage.

Panelling: In large sized cans the body may become forced inwards by atmospheric pressure, if there is very high vacuum in the can. This condition is called panelling.

Chemical causes

One of the main chemical causes of spoilage in canned foods is the reaction between the food and the materials of the can. This interaction can generate hydrogen gas and release metal ions, which increases the metal content in the product. Although the food may remain safe to eat, the presence of hydrogen gas can make it undesirable to consumers. Excess heat processing also leads to non-enzymatic browning reaction resulting in brown discolouration and charring.

- Sulphur-metal reactions can also occur if lacquering is poor
- Food–metal reaction:
    - Acids in food react with tin/iron.
    - Produces hydrogen gas → swelling of can, metallic taste, higher metal content in food.
    - Food may still be safe, but consumers may reject it.
- Excess heat processing:
    - Causes non-enzymatic browning reactions.
    - Leads to brown discoloration, burnt flavour, or even charring of food.

Microbial causes

Flat sour spoilage: Caused by Bacillus species, produces acid without gas, especially in low-acid foods.

Can appears flat but content tastes sour.

- TA spoilage (Thermophilic anaerobic): Caused by *Clostridium thermosaccharolyticum*, produces acid and gases (CO_2, H_2), swelling cans with butyric or cheesy odors.

Occurs if cooling/storage is inadequate**.**

- Sulphide spoilage (Sulfur stinker): Caused by *Desulfotomaculum* and Clostridium species producing hydrogen sulfide gas, rotten egg odor, black colonies (due to iron sulfide), no can swelling. Indicates under-processing.
- Sulfide "Stinkers": *Desulfotomaculum nigrificans* (previously called *Clostridium nigrificans*) is a heat-loving, anaerobic bacterium known to cause sulfide stinker spoilage. This organism produces hydrogen sulfide during spoilage, leading to an unpleasant odor and discoloration of the food. It is the only sulfur-reducing bacterium known to spoil foods that have undergone thermal processing
- Mesophilic Spore-Forming Bacteria Spoilage
  Mesophilic Clostridium species cause spoilage by fermenting sugars to acids and gases, resulting in gas formation and can swelling. Proteolytic Clostridia degrade proteins releasing foul-smelling compounds like H_2S, mercaptans, ammonia. Bacillus species spoilage often due to contamination after heat treatment or insufficient processing**.**

Non-Spore-Forming Bacteria Spoilage

- Presence indicates improper heat treatment (e.g., pasteurization) or leakage. Thermoduric bacteria like *Enterococcus*, *Streptococcus thermophilus*, *Micrococcus*, and *Lactobacillus* can survive mild heat or enter via leaks. These bacteria may cause gas production (swelling) and acidification.

Yeasts and Molds in Spoilage

- Yeasts ferment sugars producing CO_2, causing swelling in acidic canned foods like fruits and jams. Molds spoil surface of home-canned products, especially with high sugar concentrations. Mold growth leads to off-flavors, discolorations, and texture changes. (Wilson, 2023).

Under-processing

A second major cause of canned food spoilage is under-processing, which can occur for several reasons:

- Insufficient heat treatment to destroy key microorganisms.
- Abnormally high levels of contamination from typical spoilage organisms.
- Faulty operation of the retort.
- Malfunctioning instruments attached to the retort.
- Presence of air inside the retort due to incomplete venting.
- Variations in product consistency, incorrect filling in terms of solids-to-liquid ratio, headspace, or excessive solid content.
- Low initial temperature of the product before processing.

Post-Processing Spoilage

Another form of microbial spoilage is post-processing spoilage, which results solely from can leakage. Common causes include:

- Poorly sealed double seams.
- Rapid changes in pressure during retorting.
- Physical damage at the double seam area.

When water enters the can during cooling, microorganisms present in that water can contaminate the food. In some instances, a leaking can may reseal on its own, and gas production inside can cause it to bulge- a condition referred to as *leaker spoilage*. These cans can harbor mixed populations of spore-forming and non-spore-forming bacteria.

The risk of this spoilage can be reduced by adding 4–7 ppm of free chlorine to cooling water. Air cooling generally results in less spoilage compared to water cooling. Using UV-sterilized water alongside chlorine treatment is a modern enhancement to control contamination (Hernandez et al., 2025).

Problems (spoilages) in canned marine products

- Sulphide blackening
- Curd or adhering
- Blue discolouration
- Honey combing
- Struvite formation
- Retort burn
- Case hardening
- Mush

Sulphide blackening or iron sulphide blackening

It is most commonly observed in canned shrimp, lobster, crab less commonly in other products etc. Though the cans are coated with sulphur-resistant lacquer, any imperfection in the lacquer coating during its manufacture or subsequent reforming or any scratches during handling expose the tin layer and trimethyl amine present in marine products dissolves tin layer exposing iron.

Uniform lacquering of can, its careful handling and use of parchment paper while packing can minimise this problem.

Curd or adhesion

Curd is salt-soluble coagulated or precipitated protein and often found at the top of canned Salmon or Mackerel. This problem is more in fish canned in natural style or without precooking. The curd may adhere to can surface and the lacquer may get peeled off when the curd is removed. The reasons for curd formation are use of less fresh fish, inadequate brining and precooking. This can be prevented by cold blanching of fish (brining) in 10-15% brine for 20-30 minutes and subsequent washing.

Blue discolouration

This issue is commonly seen in canned crab meat, particularly in portions of the body with poorer blood circulation compared to the legs or claws. Such areas tend to show higher levels of bluish coloration. The effect is caused by haemocyanin present in crab blood reacting with sulfur compounds during heat processing, forming blue copper sulfide. When copper content in the meat exceeds 2 mg per 100 g, the problem becomes noticeable. Thorough bleeding of crabs during preparation can help reduce copper levels to below 2 mg%, thereby minimizing discoloration.

Brown Discoloration

Brown coloration develops when proteins or amino acids interact with lipid oxidation products. It is observed in many processed fish species, including white pomfret and sardines. This protein-lipid browning is more pronounced in fatty fish than in lean varieties.

Honey Combing

Honey combing occurs in canned tuna made from stale raw material, giving the meat a porous, honeycomb-like appearance. It can be prevented by using fresh tuna and thawing frozen material slowly, with minimal rough handling.

Struvite Formation

Some canned marine foods like brine-packed shrimp, crab, and tuna may contain glass-like crystals composed of magnesium ammonium phosphate hexahydrate [$MgNH_4PO_4 \cdot 6H2O$]. These form when the meat's pH exceeds 6.8. Although struvite is harmless, colorless, odorless, and transparent, larger crystals can resemble broken glass, making them undesirable to consumers. Rapid cooling leads to smaller crystals that are less noticeable. Adding chelating agents such as sodium hexametaphosphate or EDTA can prevent crystal formation. Factors contributing to struvite include the use of hard water, poor-quality raw material, and magnesium impurities in salt used during canning.

Retort Burn

This defect, often found in canned shellfish such as clams, mussels, and oysters, occurs when there is insufficient liquid or packing medium to completely cover the meat during processing.

Case Hardening

High temperatures and excessively rapid heating can dehydrate the surface of fish meat, creating a hard outer layer.

Mush

"Mush" refers to an overly soft, weak-textured condition in certain pilchards caught at the end of their spawning season. It is caused by the parasitic protozoan *Chloromyxum*, which breaks down fish tissue during storage, leaving the meat excessively soft inside the cans (Martin & Gupta, 2024).

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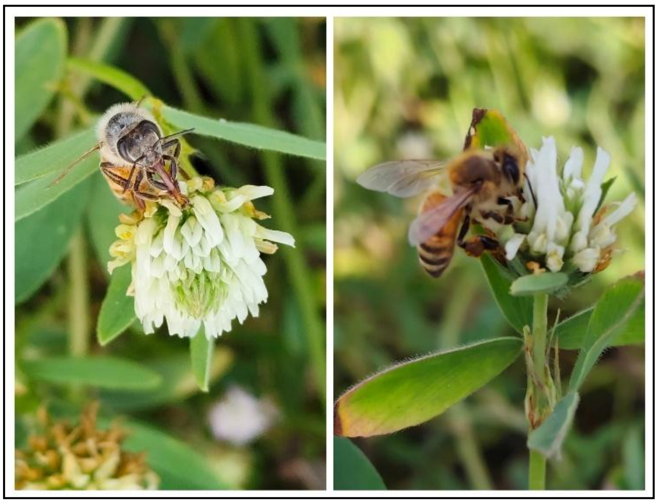
THE SWEET SCIENCE OF HONEY: HOW BEES TURN NECTAR INTO LIQUID GOLD

Diksha Kushwaha, Usha*, Akhilesh Kumar Singh and Priyanka Kaundal

Department of Entomology, Rani Lakshmi Bai Central Agriculture University,
Jhansi, Uttar Pradesh-284003
*Corresponding Email: ushamauryaentomology@gmail.com

Introduction

Honey bees (*Apis mellifera*) are crucial managed pollinators, enhancing crop yields and sustaining biodiversity (Aizen & Harder, 2009). Beyond pollination, bees produce valuable products like honey, wax, royal jelly, propolis, and venom (Wang *et al*., 2014). Honey, a complex nectar-derived product, owes its high energy density and storability to its primary monosaccharides, fructose (38%) and glucose (31%), alongside low water activity (White & Doner, 1980). Rich in amino acids, vitamins, minerals, phenolic compounds, and enzymes like glucose oxidase, honey's biochemical composition imparts preservative and bioactive qualities (Bogdanov *et al*., 2008; Alzahrani *et al*., 2012)."Liquid gold," honey's colour, economic value, and health benefits reflect its rarity bees must visit over two million flowers to produce one pound (Crane, 1990). With a history of use across ancient civilizations for food, medicine, and rituals, honey's preservative qualities, cultural significance, and microbial inhibition are well-documented (Eteraf-Oskouei & Najafi, 2013; Bogdanov *et al*., 2008). Nutritionally, its high sugar content provides rapid energy, while its antimicrobial properties due to low water activity, acidic pH, and hydrogen peroxide-producing enzymes suppress pathogens like *Staphylococcus aureus* and *Escherichia coli* (Mandal & Mandal, 2011). Research highlights honey's antioxidant, anti-inflammatory, and wound-healing effects, affirming its medicinal relevance. Ecologically, honeybee pollination supports biodiversity and agricultural productivity, emphasizing honey's economic and environmental importance (Klein *et al*., 2007).



The Role of Bees in Honey Production

Honeybee Species: The genus *Apis* includes several honey-producing species, with *Apis mellifera* (Western honeybee) being the most widely used for commercial honey production due to its high yield and ease of management (Crane, 1990). Other species like *Apis cerana*, *Apis dorsata*, and *Apis florea* also produce honey but are less common commercially. *Apis cerana* is primarily domesticated in Asia, while *Apis dorsata*, or the giant honeybee, produces honey in open combs and is unsuitable for domestication due to its aggressive behavior (Oldroyd & Wongsiri, 2006; Hepburn & Radloff, 2011).

Nectar Collection: The Foundation of Honey Production

Honey production commences when forager bees collect nectar from blossoms and store it in their specialized honey sacs prior to returning to the hive. This nectar is predominantly composed of sugars such as sucrose, glucose, and fructose, along with trace amounts of proteins and amino acids. Bees display a behavior referred to as flower constancy, which indicates that they consistently visit the same species of flowers, thereby enhancing pollination and affecting the unique flavor of honey (Giurfa, 1993). Upon their return to the hive, the foragers transfer the nectar to worker bees via trophallaxis, a process during which enzymes alter the nectar and reduce its water content, ultimately transforming it into honey (Seeley, 2009).

Conversion to Honey

Enzymatic activity, dehydration, and microbial inhibition are the key processes that transform nectar into honey. Enzymes such as invertase, sourced from the hypopharyngeal glands of bees, facilitate the hydrolysis of sucrose into glucose and fructose as nectar is exchanged among bees, thereby enhancing the sweetness and stability of honey (Barker & Lehner, 1974; White & Doner, 1980). Another crucial enzyme, glucose oxidase, generates hydrogen peroxide and gluconic acid from glucose, resulting in an acidic pH (3.2–4.5) and imparting antibacterial properties (Weston, 2000). The generation of hydrogen peroxide further inhibits harmful microorganisms, thereby prolonging the shelf life of honey.

Subsequently, worker bees utilize their wings to evaporate the moisture content of the nectar to between 17–20%, which aids in stabilizing honey. This reduced water content, along with its acidity, effectively hinders microbial proliferation, rendering honey a durable, energy-rich food source for bees and a significant asset for human co

Source : https://beeprofessor.c om/how-do-bees-make-honey/

The Chemistry of Honey

Honey is a naturally complex substance, primarily composed of simple sugars, with glucose and fructose accounting for 70–80% of its sugar content. Glucose constitutes around 30–35%, and fructose 35–40%, lending honey its sweetness and ease of digestion (White & Doner, 1980; Bogdanov *et al*., 2008). This high sugar concentration, along with a water content of 17-20%, contributes to honey's energy density and stability. In addition to sugars, honey contains trace vitamins (B vitamins like niacin, riboflavin, pantothenic acid) and minerals (calcium, magnesium, potassium, iron) (Weston, 2000). It also includes amino acids, particularly proline, which influences honey's aroma and flavor (Almeida-Muradian *et al*., 2005), as well as polyphenols like flavonoids and phenolic acids, which provide antioxidant benefits (Bogdanov *et al*., 2008; Alzahrani *et al*., 2012). Honey's composition varies with botanical and geographical factors (Bertoncelj *et al*., 2007).

Honey's antibacterial properties stem from its low water content, acidic pH (3.2–4.5), and hydrogen peroxide. With water activity below 0.6, honey creates a hyperosmotic environment that dehydrates bacteria (Molan, 1992). The acidity, due to gluconic acid produced from glucose by glucose oxidase, further inhibits bacterial growth (Bogdanov *et al*., 2008). Additionally, hydrogen peroxide, introduced during nectar processing by honeybees, provides sustained antibacterial action, making honey effective for wound care. Manuka honey's non-peroxide agent, methylglyoxal, also enhances its antibacterial activity (Al-Waili *et al*., 2011; Mavric *et al*., 2008).

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Tor tor MAHSEER OF THE NARMADA: BIOLOGY, FISHERY, AND CONSERVATION CHALLENGES

Shashi Bhushan[1]*, Dhalongsaih Reang[2], Harsha Haridas[1], Dayal Devdas[3], Layana P[3] and Hasan Javed[1]

[1]ICAR-Central Institute of Fisheries Education, Powarkheda Centre, Madhya Pradesh.
[2]ICAR-Central Institute of Fisheries Education, Kolkata Centre, West Bengal
[3]ICAR-Central Institute of Fisheries Education, Versova, Mumbai, Maharashtra, India
*Corresponding Email: shashi@cife.edu.in

Introduction

Tor tor is the most common Himalayan Mahseer and very attractive sport fish. The group name 'Mahseer' is referred for its big-size scale and head length, however, the probable derivation is from the Persian 'mahisher'(Lion like head) for its fighting and sporting characters (Desai, 2003). Mahseer is often used for the fish species belonging to genera *Tor*, *Neolissochilus* and *Naziritor.* It is called as 'King of Indian Aquatic Systems' from Indian sub-continent (Langer *et al.*, 2001). Mahseer prefer fast-flowing rocky streams with crystal clear freshwater and high oxygen content. It can attain a very large size up to 54 kg (Froese & Pauly, 2003).

The big-scaled cyprinid fish, Mahseer, *T. tor* is one of the mighty highly prized and esteemed fish of India, it is the native of several major river systems in India all along the sub-Himalayan range including Ganga, Yamuna, Ghagra, Gomti, Rapti, Sarda, Ramganga, Kosi, Sone, Rihand, Chambal, Ken, Betwa, Mahanadi, Narmada, Tapti, Mahi, Brahmputra-Barak river system, Indus, Sutlej and river Beas spread over the states of Uttar Pradesh, Bihar, Haryana, West Bengal (Darjeeling), Assam, Madhya Pradesh, Himachal Pradesh, Punjab and Uttaranchal. Besides neighboring countries like Nepal, Bhutan, Pakistan, Bangladesh, Myanmar and China (Jayaram, 1999; Desai, 2003). Although it is available in Himalayan Rivers; it is the important fisheries resources of the river Narmada especially in the Madhya Pradesh. River Narmada often referred as "Life Line of Madhya Pradesh" is habitat for large number of fishes (Sharma *et al.*, 2014a).

Tor tor is state fish of Madhya Pradesh, commonly known as Badhas. During NBFGR-NATP workshop held at Lucknow, Mahseer was identified as a highly important fish having sport, food and high economical value (Ponniah & Sarkar, 2000) and later on was declared as the State Fish for Madhya Pradesh (India). It fetches best market price of 300-600/kg in fish market of Narmadapuram (Madhya Pradesh).

Systematic classification of the tor Mahseer, *Tor tor*
Kingdom: Animalia
Phylum: Chordata
Class: Actinopterygii
Order: Cypriniformes
Family: Cyprinidae
Genus: *Tor*
Species: *Tor tor* (Hamilton, 1822)

Figure: Adult *Tor tor* from Dongarwada Ghat (Narmadapuram District) Narmada River, Madhya Pradesh

In India, several aspects of Mahseer have been studied by a number of investigators, however, very little work have been done on *T. tor.* Although some preliminary observations of Indian Mahseer were reported in early nineties (Cordington & De, 1939), the sporting and fighting characters of Mahseer was highlighted by Thomas (1897) and Hora (1939, 1940). This species has been categorized as endangered (Anon, 2001; Sharma, 2003) during the Conservation Assessment and Management Plan (CAMP, 1998), however, as per IUCN (2010), the fish has been declared as near-threatened (NT)(Rayamajhi et al., 2010).

It inhabits riverine pools and lakes and also in stream with good flow and rocky bottom where they attain the best growth. They are benthopelagic occurs in a tropical freshwater habitats at depths of 15-30 meters. They show migration upstream to downstream for breeding and feeding. Adults are omnivorous in nature. They feed on insect, mollusks, zooplankton, debris, sand, mud, fish scale and bone, chronomid larvae, water beetles, crustacean ,filamentous algae and macrophytes. Juveniles mainly consume insect (Desai, 2003) The protrusible and suctorial mouth of Mahseer (*T. tor*) show preference for insect larva and mollusks suggesting its bottom feeding habit. The suctorial action of the mouth has ability to rapidly suck up bottom food (Thomas, 1873). Among Indian Mahseers*, Tor tor* (Hamilton, 1822) is the most important food and game fish of India after *Tor putitora* (Hamilton, 1822). This fish is famous for its fighting character during angling and because of its exclusive good taste; it is ranked on the top of all commercial catches of river Narmada. *T. tor* is a potential candidate for the development of open water fishery as well as aquaculture.

Status of the *Tor tor* Mahseer in Madhya Pradesh

Efforts has been made by NBFGR to assess the threat status of Indian freshwater fishes for conservation at national and regional level (Lakra & Sarkar, 2007; Lakra *et al.*, 2010) and accordingly, Mahseer (*T. tor*) was considered the status of endangered and suggested for timely action for conservation failing which it may disappear for our future generation (Mahanta *et al.*, 1998). Decline in the population of Mahseer was observed by several workers throughout the country (Sandhu *et al.*, 1994; Mahanta *et al.*, 1998; Bhatt *et al.*, 1998a; Nautiyal *et al.*, 1998, 2008;Kumar, 2000; Menon *et al.*, 2000; Ogale, 2002a,b,c; Malik& Negi, 2007; Dinesh & Nandeesha, 2007; Kalita *et al.*,2007; Oliver *et al.*, 2007; Vinod *et al.*, 2007; Chalkoo *et al.*,2007). The IUCN Red data list of 2018 identified this fish as data deficient. The uncertainty of identity is the reason for the IUCN Red Listing status of Data Deficient. The main reasons for decline of this population is fast degradation of aquatic ecosystems, indiscriminate fishing of brood stock and juveniles, barrages and weirs and other anthropogenic interventions /intrusions. Constructions of dams are the main factor responsible for Mahseer decline as it restricts the pathway of Mahseer migration (Shrestha, 1997; Mahanta *et al.*,1998; Malik & Negi, 2007).This fish was once abundant in river Narmada and attracted anglers from India and abroad but due to overexploitation, its availability is meagre and status declared as near threatened (Nguyen *et al.*, 2006; Rayamajhi *et al.,*2010). There is decline in the catch record of *T. tor* from Madhya Pradesh (Tamot 2007). The catch data of *T. tor* had considerably declined and ranged between 10-15% of total fish catch in Narmada River around Narmadapuram (Somdutt *et al.*, 2007). Severe overfishing and population decline of Mahseer (*T. tor*) from Narmada River were also observed by several workers (Bhatt *et al.*, 2004; Desai, 2003; Nautiyal *et al.*, 2008). Construction of dams across river Narmada is considered to be the main reason for the decline of Mahseer. The population of *Tor tor* is rapidly declining in Narmada River due to commissioning of around 25 large dams (leads to the changes in the ecological and hydrological parameters of the river), destructive fishing practices, illegal sand mining, boulder removal, pollution and climate change. Survey report (1958-1967) by ICAR-CIFRI (Karmchandani *et. al,* 1967), indicates the presence of 25-30% of the fishes from the Narmada River includes the *Tor tor,* where as it was declined to only 3% in 2017 (Saxena & Desai, 2017).

Several attempts were made by State Government and Madhya Pradesh Fisheries Federation for the conservation and protection of this precious fish. A Mahseer hatchery was established in Harda district for the breeding of Mahseer. In 2012 about 57,000 seed of *T. putitora* brought from Bhimtal of the size range 40-50 mm was introduced into cages fixed at Kerwa dam, Bhopal by Fisheries Federation which yielded encouraging results as fishes grew upto 120mm in four months. Within a period of two years around 80,000 seeds of different species of Mahseer collected from different parts of the country were introduced into several dams in Madhya Pradesh by Fisheries Federation to conserve and promote Mahseer as sport fish. Several seed collection centers were identified on river Narmada for *T. tor* seed collection. Dongarwadaghat near Narmadapuram and a tributary that comes out from Rawatbhata dam on river Chambal in Mansor district are the two sites in Madhya Pradesh where good quantity seed of *T. tor was* available. Breeding and rearing of *Tor tor* was successfully achieved in Bargi Dam and Mandla dam by department and good size of fingerlings were released into the Narmada River. Mahseer migrate up streams during June-August for breeding, it was observed that during this period fishermen fixed pahoo trap (a sort of barricade) to catch the big sized fishes (brooders) when fishes move for breeding they get caught into the trap and killed before releasing the eggs and stocking new recruits. This is one of the reasons identified for declining Mahseer population in river Narmada.

Biology of *Tor tor* Mahseer

Food and feeding Habit:

The Mahseer fish is categorized as Omnivorous feeder because of the presence of the wide range of the food items in the gut of the fish, which is well supported by the presence of the protrusible and suctorial mouth. This fish species is a marginal feeder which mainly feed on bottom of the water bodies. The majority of the gut content includes Insect larvae, small molluscs, and macrophyte along with Sand and mud in almost all the stomach. The shape of the mouth helps in the sucking up the bottom foods and macrophytes.

It also feeds on aquatic plants, crabs, earthworms, insects, shrimps and found that very little food (Thomas (1873). The pharyngeal teeth help in masticating food contents (Hora, 1940).
In the Narmada River, the diet of *Tor tor* was primarily composed of macrophytes (48.5% of the total volume), followed by filamentous algae (14.5%), molluscs (10.5%), insects (8.3%), debris (7.9%), and sand and mud (7.8%). Aquatic macrophytes comprised the predominant component at 57.5%, followed by molluscs at 36.2%, sand and mud at 34.6%, insects at 32.8%, filamentous algae at 25.1%, and detritus at 14.8% (Desai, 1982). Occurrence of sand and debris in the gut indicates the bottom feeding habit. Gupta *et al.,* (1991) studies on the food and feeding habit of *Tor putitora* (Hamilton) by the analysis of gut content and relative length of gut (RLG) value. They show that the *Tor putitora* (Hamilton) was an omnivore. It can be regarded as various feed sustaining mainly on vegetable matter and insect during gut content analysis.

Table: Gut Component composition of *Tor tor* (Desai, 1970)

Broad group of Gut contents	Volume (by eye estimation)	Occurrence method	Index of Preponderance
Macrophytes	48.5 (1)	57.5 (1)	66.37 (1)
Molluscs	10.5 (2)	36.2 (2)	9.03 (2)
Algae	14.5(3)	25.1 (3)	8.67 (3)
Insects	8.3 (4)	32.8 (4)	6.52 (4)
Sand and Muds	7.8 (5)	34.6 (5)	6.39 (5)
Debris	7.9 (6)	14.8 (6)	2.79 (6)
Fruits	2.1 (7)	4.4 (7)	0.22 (7)
Fish Scales, Bones	0.2 (8)	1.6 (8)	0.01 (8)
Unidentified Items	0.2 (9)	0.7 (9)	Neg. (9)

Figure: Open Gut cavity of *Tor tor* from Narmada River, Madhya Pradesh

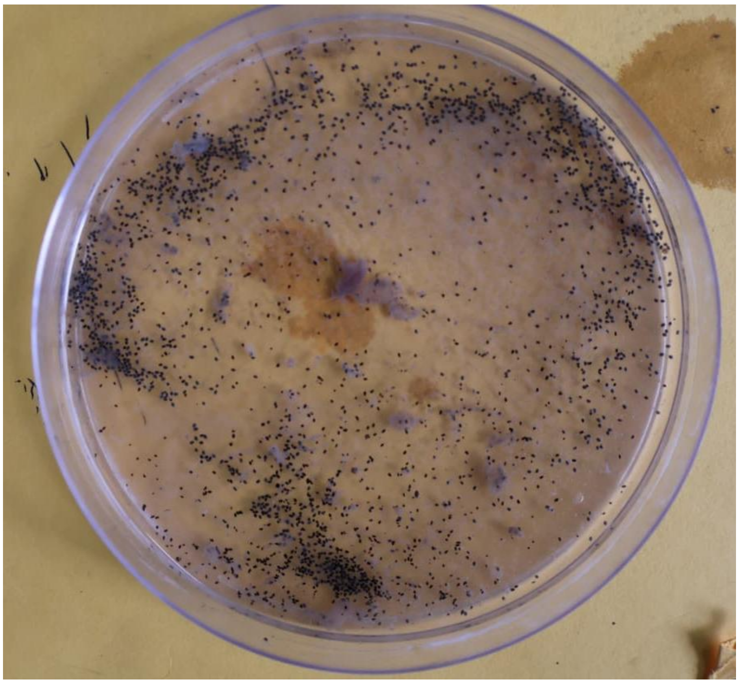

Figure: Debris and mud content in the dissected stomach of *Tor tor*, Mahseer

Reproductive study of *Tor tor,* Mahseer

Desai *et al.,* (1972), study mainly on the maturity, fecundity, and larval development of *Tor tor*. The breeding habits of *Tor tor* from the river Narmada were studies for a period of three years on the basis of gross examination of gonads, gonadosomatic index (GSI) and ova diameter. The breeding season of *Tor tor* commences in July and continues till February-March. The peak breeding was observed in July to September. The individual fish was found to breed in four act extending over a period of 2-3 month. The length frequency study of fry also indicate that the breeding period extend from July to March. *Tor tor* attains maturity over 360 mm in total length. The fecundity is varied from 9330 to 1,35,470 in the range of 283-750 mm. They observed 5 larval stage of *Tor tor.*

Figure: Ovary of Female *Tor tor*, collected from Narmada River Madhya Pradesh

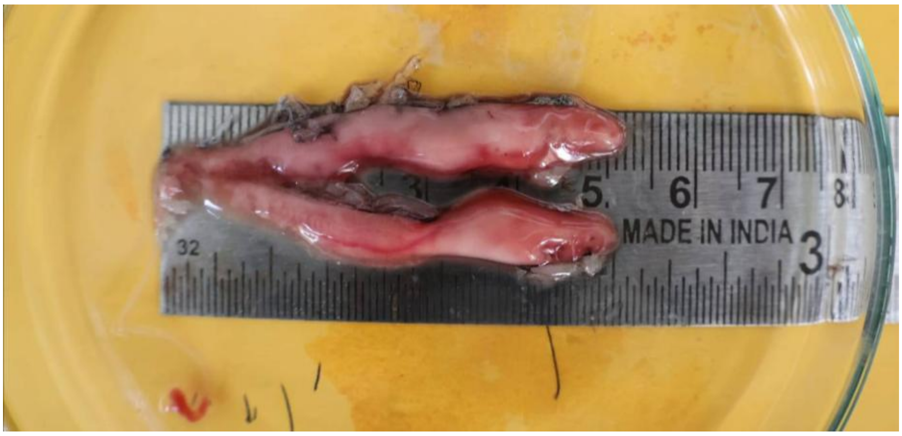

Figure: Immature Testes of *Tor tor*, collected from Narmada River Madhya Pradesh

Table 2. *Maturity scale of* *Tor tor* ***(female) (Desai, 1973)***

ICES (Wood, 1930)		*Tor tor*
Immature (Stage A)	I	Ovary slender, thin, short, whitish and ribbon-like, ova minute, transparent and not visible to naked eye, some devoid of yolk deposition while in some yolk deposition just commenced; frequencies with one mode, maximum ovum diameter = 0.57 mm; common all the year round.
Maturing (Stage B)	II	Ovary slightly enlarged and becoming translucent; yolk deposition further progresses and ova become yolky, opaque and visible to naked eye; frequencies with two modes, maximum ovum diameter = 0.76 mm; common from December to April.
Maturing (Stage C, D, E, & F)	III	Ovary turns yellow and becomes thickened on all sides, ova have granular appearance and are visible to naked eye; frequencies with two to five modes, maximum ovum diameter = 1.33 mm; common from December to April.
Mature (Stage G)	IV	Ovary greatly enlarged with large mature eggs still contained within the ovarian follicle and not free; frequencies with five modes, maximum ovum diameter = 1.90 mm; common from April to June.
Mature (Stage H)	V	Ovary appears like a yellow bag of cellophane paper containing large, yellow, free and mature ova; frequencies with five modes, maximum ovum diameter = 2.28 mm; common from June to September.
Partly spent (Stage I, J, K & L)	VI	Ovary reduced in size posteriorly, slightly bloodshot and flaccid owing to expulsion of some mature eggs, few mature eggs still present for subsequent spawning frequencies. Initially with five modes but subsequently with three modes; common from August to October.
Spent (Stage M)	VII	Ovaries become flabby, further contracted, appear like a wrinkled, collapsed sacs with leathery wall in contrast to the parchment-like wall of distended ripe ovary; frequencies with two modes, sometimes showing insignificant modes of mature and degenerating ova; common from October to November.

Exploitation of *Tor tor:*

The *Tor* Mahseer along the Narmada River in the Madhya Pradesh is mainly caught by Gill Net, Cast net and Hook and Line and Drag Net. Operated form the various small and large boats.

Fishing crafts:

The fishing craft which are used to catch Mahseer in Narmada River are; Dug-out canoe, Plank–built boat, Bamboo raft, Large boat and Wooden frame iron/tin/aluminum sheet boat.

Dug-out canoe: Dug-out canoe is locally known as 'Donga' which are small wooden canoes dug-out from a single log of wood. The overall length of 3-4m and width of 0.5-0.6 m are common; which can accommodate only 1 or 2 fishers at a time.

Plank built boat: It is commonly called as 'Nao', 'Lauka' and 'Nauka'. It is spindle shaped and constructed by joining good quality wooden planks with iron nails. Periodical coating of coal and kerosene oil is done in the bottom part of the boat to preserve from fouler and borers. The size of the fishing boats varies to a range of 5-7m with a width of 1-1.5m, usually being operated by 2-4 fishermen.

Fishing Gears: The dominant gears which are in used in Narmada River are Gill net, Cast net, Drag net, Scoop net, Hand bag net for jumping fish, Hook and Line and Traps.

Gill net : The gill net is most common and abundant net used all along the Madhya Pradesh to catch Mahseer and other fisheries resources. The gill nets are locally called as 'Phansa/Phansi Jal' or 'Phanda Jal'. The Length, Breadth and mesh size of the net varies according to depth of the river and topography of the river. Gill net of about 3 -10 m width and 100- 200 m in length are commonly used.

Drag net: Mostly used in shallow waters; locally called as Maha Jal. The net is towed through the water and the mesh size varies from 20-60 mm. It can be towed along the shore or can be tied with two boats together.

Cast net: It is conical in shape with a strong rope which is attached to the apex; forming a circle when spread out. Cast net is locally known as 'Phenka Jal'. A number of lead or iron weights are attached along the margin to sink it during the operation. This type of net is mostly used by small and marginal fishermen and the catch is sold in fresh condition to the local vendor or sold by fishermen itself in the local market.

Scoop net: It is a conical shaped bag net, mostly used in shallow waters and Small reservoirs.

Hand bag net for jumping fish: It is a square or rectangular-shaped miniature handbag netted onto a frame constructed from wood, bamboo, or cane. It is affixed to an elongated handle for maneuvering the net. The square or rectangular frame, equipped with mosquito netting, is utilized to capture fish from a considerable distance when they leap from the water. This particular style of bag net is referred to locally as 'Jhalga.'

Reason for decline of *Tor tor* in Narmada River, Madhya Pradesh:

The decline of *Tor tor* in the Narmada River, Madhya Pradesh, can be attributed to a combination of human-induced factors and environmental degradation. These are :

1. Overexploitation of the resources: Overexploitation of resources is one of the primary reasons for the decline of *Tor tor* in the Narmada River. Due to its high economic and cultural value, this species has been extensively targeted by local fishermen for food and commercial purposes.

Continuous and excessive fishing pressure, especially during breeding seasons, has drastically reduced its population and disrupted its natural reproductive cycle. The removal of large, mature individuals—which are crucial for maintaining genetic diversity and population recovery—has further accelerated the decline. Without proper regulation and enforcement of fishing limits, the unsustainable harvesting of *Tor tor* continues to threaten its long-term survival in the Narmada River ecosystem.

2. Destructive fishing practice: Destructive fishing practices have played a significant role in the decline of *Tor tor* in the Narmada River. Methods such as the use of explosives, poisons, and fine-meshed nets not only kill large numbers of fish indiscriminately but also destroy the habitats that are vital for breeding and feeding. These harmful practices target both adult and juvenile fish, preventing population replenishment and reducing biodiversity in the river ecosystem. In particular, poisoning and dynamite fishing degrade water quality and eliminate other aquatic organisms essential for maintaining ecological balance. Over time, such unsustainable and destructive fishing activities have severely disrupted the life cycle of *Tor tor*, leading to a sharp decline in its numbers and threatening the overall health of the Narmada River ecosystem.

3. Unregulated fishing: Unregulated fishing has been a major contributor to the decline of *Tor tor* in the Narmada River. The absence of proper fishing laws, enforcement, and monitoring allows uncontrolled harvesting of this species throughout the year, including during its breeding season. Without restrictions on gear type, mesh size, or catch limits, both mature and juvenile fish are indiscriminately captured, reducing the population's ability to recover naturally. Additionally, the lack of community awareness and institutional oversight has led to the depletion of local fish stocks and increased competition among fishermen. Over time, this unregulated exploitation has disrupted the ecological balance of the river, threatening not only *Tor tor* but also other native fish species that depend on the same habitats.

4. Construction of Dams and Barrages: The construction of dams and barrages along the Narmada River has significantly contributed to the decline of *Tor tor* populations. These structures alter the natural flow of the river, fragment habitats, and obstruct the migratory routes that *Tor tor* relies on for spawning and feeding. By changing the river's flow regime, dams also affect water temperature, oxygen levels, and sediment transport—all of which are critical for the survival and reproduction of this species. The formation of reservoirs and reduced downstream flow destroy breeding grounds, particularly shallow gravel beds where *Tor tor* lays its eggs. Furthermore, fluctuating water levels caused by dam operations disrupt the timing of spawning migrations. Collectively, these impacts have led to habitat degradation and loss of connectivity, making it increasingly difficult for *Tor tor* populations in the Narmada River to sustain them.

5. Illegal sand mining and boulder removal: Illegal sand mining and boulder removal have severely affected the habitat of *Tor tor* in the Narmada River. These activities disturb the riverbed structure, which is crucial for the fish's spawning, feeding, and sheltering. *Tor tor* typically breeds in shallow, rocky, and gravelly stretches of the river, but the extraction of sand and boulders destroys these breeding grounds and increases sedimentation, reducing water clarity and oxygen levels. The removal of natural substrates also alters the river's flow pattern and destabilizes banks, leading to habitat fragmentation and loss of aquatic biodiversity. Additionally, heavy machinery used in sand mining causes noise and vibration that further disturb fish populations. As a result, illegal sand mining and boulder removal have not only degraded the ecological integrity of the Narmada River but have also played a major role in the rapid decline of *Tor tor* populations.

6. Water pollution: Water pollution is a major factor contributing to the decline of *Tor tor* in the Narmada River. The discharge of untreated industrial effluents, agricultural runoff containing pesticides and fertilizers, and domestic sewage has severely degraded the water quality of the river. These pollutants reduce dissolved oxygen levels, increase toxic substances, and alter the chemical balance of the aquatic environment, making it unsuitable for sensitive species like *Tor tor.* Contaminated water affects the fish's health, growth, and reproductive success, often leading to increased mortality rates and developmental abnormalities. Nutrient enrichment from agricultural runoff also causes eutrophication, leading to algal blooms that further deplete oxygen levels. Over time, persistent pollution has not only diminished *Tor tor* populations but has also disrupted the overall ecological balance of the Narmada River ecosystem.

7. Microplastics pollution: Microplastics pollution has recently emerged as a significant threat to *Tor tor* in the Narmada River. These tiny plastic particles, originating from the breakdown of larger plastic waste, synthetic fibers, and personal care products, accumulate in the river system and are easily ingested by fish. Once ingested, microplastics can cause physical injuries to the digestive tract, block nutrient absorption, and introduce toxic chemicals into the fish's body. Over time, this leads to physiological stress, reduced growth rates, and impaired reproductive performance in *Tor tor*. Moreover, microplastics can also affect the overall food web, as they are transferred through different trophic levels, impacting not only fish but other aquatic organisms as well. The increasing presence of microplastics in the Narmada River reflects poor waste management and highlights the urgent need for pollution control measures to protect *Tor tor* and preserve the river's ecological health.

Conservation of *Tor tor*, Mahseer: The conservation of *Tor tor* (mahseer) in the Narmada River requires a combination of ecological restoration, sustainable management, and community participation. One of the key steps is the enforcement of fishing regulations, including seasonal bans during the breeding period, restrictions on mesh size, and prevention of destructive and unregulated fishing practices. Habitat restoration should focus on protecting and rehabilitating spawning and feeding grounds that have been degraded by sand mining, pollution, and river engineering projects. Environmental flow releases from dams and barrages are essential to maintain the natural hydrological regime necessary for the species' migration and reproduction. Additionally, strict control of industrial discharge, agricultural runoff, and plastic waste is crucial to improve water quality. Establishing fish sanctuaries and breeding centers can also help restock wild populations through scientific hatchery programs. Most importantly, involving local fishing communities in awareness campaigns, sustainable livelihood programs, and participatory conservation initiatives can ensure long-term protection of *Tor tor* while maintaining the ecological integrity of the Narmada River.

Initiative of the Fisheries Department of Madhya Pradesh for the conservation of *Tor tor.*

1. **Seed / fry stocking and hatchery programs:** The Federation has been involved in purchasing and stocking mahseer seeds from established hatcheries — for example, around 2 lakh seeds were bought for conservation work in the state.

2. Habitat protection and sanctuary / site-designation efforts: The Federation, together with the state biodiversity board, has worked to identify key habitats and proposed declarations of certain stretches (e.g., parts of the Narmada) as “fish sanctuaries” or biodiversity heritage spots to safeguard mahseer habitat. They have also asked fishermen to release mahseer that are caught inadvertently (in nets or hooks) to reduce mortalities of wild individuals.

3. Stakeholder engagement & policy campaigns: Under campaigns such as the Mukhyamantri Matsya Vikas Yojana, seeds of mahseer are to be released in tributaries like Denwa and Tawa, with support from the Federation and fisheries department. Fishermen are engaged via advisories (for example, asking them to release mahseer) and habitat mapping through GIS by the forest/fisheries departments.

4. Scientific & genetic monitoring: A specific protocol: ICAR-NBFGR demonstrated milt cryopreservation technology for *Tor tor* in collaboration with the Federation’s seed farm at Bargi Dam, Jabalpur. This helps maintain genetic material for future restocking. The cryopreservation work (via ICAR-NBFGR) points to long-term genetic conservation being supported. Also, mapping of occurrences and genetic/morphometric research on *Tor tor* is underway (involving hatcheries visited by external organizations) to resolve taxonomic identity and proper stock management. The Federation’s hatchery sites form part of these studies.

Summary

The decline of *Tor tor* in the Narmada River, Madhya Pradesh, is driven by several human-induced and environmental factors. Overexploitation, destructive and unregulated fishing, and habitat loss due to dams, barrages, and illegal sand mining have severely reduced their population. Water pollution and emerging threats like microplastics further degrade their habitat and affect survival and reproduction. To counter this, the Fisheries Department of Madhya Pradesh has initiated conservation measures including hatchery-based seed stocking, habitat protection, fish sanctuaries, community awareness programs, and scientific monitoring such as genetic preservation. These efforts aim to restore populations, safeguard habitats, and ensure the long-term survival of *Tor tor* while maintaining the ecological integrity of the Narmada River.

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ROLE OF BENEFICIAL INSECTS TO ENHANCE THE PRODUCTION OF FIELD CROPS IN RABI SEASON

Roushani Singh[1] and Radheshyam Dhole[2]

[1]B.Sc. (Hons.) Agriculture, Narayan Institute of Agricultural Sciences,
Gopal Narayan Singh University, Jamuhar, Rohtas, Bihar- 821305
[2]Assistent Professor, Department of Entomology,
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Rohtas, Bihar- 821305
*Corresponding Email: nias.radheshyam.dhole@gnsu.ac.in

Abstract

Beneficial insects play a crucial role in sustaining agricultural productivity, particularly during the Rabi season when major field crops such as wheat, mustard, chickpea, lentil, linseed, and vegetables are grown across diverse agro-climatic zones. These insects contribute to crop production through pollination, natural pest suppression, soil health improvement, and ecosystem regulation. Beneficial groups include pollinators (honeybees, bumblebees, solitary bees), predators (ladybird beetles, lacewings, syrphid flies, spiders), parasitoids (Trichogramma spp., Bracon spp., Apanteles spp.), and decomposers (dung beetles, termites in moderation). Their services enhance crop yield, quality, and sustainability, while reducing excessive dependence on chemical pesticides. However, populations of beneficial insects are threatened by monocropping, habitat loss, pesticide misuse, and climate variability. Understanding their presence, identifying species, and developing integrated conservation strategies are essential for promoting biodiversity-based agriculture. This article examines the major types of beneficial insects found in Rabi crops, their roles, methods of detection, habitat management practices, and biological control techniques. Future prospects include ecological engineering, precision conservation technologies, and breeding crop varieties that support natural enemies. This review aims to highlight the importance of beneficial insects in enhancing productivity and ecological sustainability of Rabi season cropping systems.

Key words: Beneficial insects, Production, Field crop and Ecological sustainability

Introduction

The Rabi season, spanning from October to April, is characterized by the cultivation of crucial field crops such as wheat, mustard, chickpea, pea, lentil, garlic, onion, fenugreek, and several leafy vegetables. These crops contribute significantly to nutritional security and farm income. While insect pests remain a major threat to crop production, the agricultural ecosystem also hosts numerous beneficial insects that perform essential ecological functions. Their role often goes unnoticed, yet they contribute immensely to crop health and productivity.

Beneficial insects help in pollination, natural pest control, nutrient cycling, decomposition, soil aeration, and ecological balance. Pollinators improve seed set and yield in cross-pollinated crops like mustard, coriander, fennel, and various vegetables grown in the Rabi season. Predators and parasitoids naturally regulate pest populations such as aphids, caterpillars, whiteflies, and leaf miners, reducing the need for chemical pesticides. By promoting beneficial insects, farmers can reduce production costs, enhance crop quality, and foster environmental sustainability.

This article presents a detailed account of beneficial insect groups associated with Rabi crops, their significance, identification and detection methods, conservation strategies, and role in integrated pest management (IPM). Special emphasis is given on ecological approaches that enhance beneficial insect activity in field ecosystems.

Major Beneficial Insects of Rabi Season Crops

1. Pollinators

Honeybees (*Apis mellifera, A. cerana, A. dorsata*)

- Crucial for mustard, coriander, fennel, niger, and vegetable seed crops.
- Increase seed yield by 20–70% depending on crop.

Bumblebees (*Bombus spp*.)

- Active in colder conditions; ideal for early Rabi crops.
- Effective in greenhouse vegetable pollination.

Solitary Bees (Megachile, Nomia species)

- Visit flowers of chickpea, lentil, and linseed.

2. Predators

Ladybird Beetles (*Coccinella septempunctata*)

- Feed on aphids, jassids, whiteflies, and mealybugs.
- Extremely valuable in mustard and vegetable crops.

Green Lacewings (*Chrysoperla zastrowi sillemi*)

- Predatory larvae devour soft-bodied pests like aphids and leaf miners.

Syrphid or Hover Flies

- Adults act as pollinators; larvae feed on aphids.
- Abundant in mustard fields.

Spiders

- Generalist predators suppress pest populations throughout the Rabi season.

3. Parasitoids

Trichogramma spp.

- Egg parasitoids of lepidopteran pests affecting wheat, mustard, vegetables.
- Bracon spp. and Apanteles spp.
- Parasitize caterpillars such as armyworms, cutworms, and bollworms.

Diaeretiella rapae

- A specialized aphid parasitoid common in mustard and crucifers.

4. Decomposers and Soil Beneficials

- Dung Beetles
- Improve soil structure and nutrient cycling.

Moderate-Termite Species

- Aid organic matter decomposition and soil aeration (in balanced populations).

Ground Beetles (Carabids)

- Predators of soil pests like cutworms and grubs.

Methods of Detection of Beneficial Insects

1. Field Scouting and Visual Observations

- Regular monitoring helps identify beneficial insects
- Look for ladybird adults and larvae on aphid-infested plants.
- Observe bees and hoverflies during flowering.
- Detect parasitized aphids (mummies) for presence of Diaeretiella.

2. Sweep Net Sampling
    - Sweep nets capture flying insects such as hoverflies, parasitoids, and bees.
    - Counts help estimate beneficial insect abundance.
3. Yellow Sticky Traps
    - While used mainly for pest detection, they also indicate the presence of parasitoids like Trichogramma.
4. Pitfall Traps
    - Useful for detecting soil-dwelling beneficials like carabid beetles and spiders.
5. Pheromone and Light Traps for Pest Monitoring
    - Indirectly help assess beneficial activity by correlating pest suppression with parasitoid populations.
6. Identification of Parasitized Hosts
    - Aphid mummies indicate parasitoid activity.
    - Dead or shriveled caterpillars show parasitoid emergence.
    - Conservation and Control Strategies to Enhance Beneficial Insects

(“Control” here refers to controlling harmful factors to protect beneficial insects.)

A. Cultural Practices

1. Crop Rotation
    - Breaks pest cycles and encourages diverse beneficial organism populations.
2. Intercropping and Border Crops
    - Mustard + chickpea or wheat + linseed intercropping enhances predator and parasitoid abundance.
3. Flowering Strips
    - Growing marigold, coriander, sunflower, and buckwheat attracts pollinators and parasitoids.
4. Reduced Tillage
    - Preserves ground-nesting bees and soil predators.
5. Maintaining Field Margins
    - Natural vegetation borders serve as refuges for beneficial insects.

B. Mechanical and Physical Measures

1. Nesting Boxes and Bee Hives

Introduce honeybee colonies (2–6 per hectare) in mustard and vegetable fields.

2. Avoidance of Broad-Spectrum Pesticides

Use selective pesticides to avoid killing beneficial insects.

C. Biological Control Approaches

1. Augmentative Release of Parasitoids

Release Trichogramma cards in vegetables and mustard.

Introduce Chrysoperla eggs for aphid suppression.

2. Use of Microbial Pesticides
Bt, Beauveria, and Metarhizium protect crops without harming beneficial insects.

D. Botanical and Organic Inputs
1. Neem Extract and Oil
Safe for bees and most predators when applied in the evening.
2. Vermicompost and Organic Manures
Enhance soil biodiversity and support predator populations.

E. Integrated Pest Management (IPM)
A successful IPM plan includes:

- Regular monitoring of pests and beneficial insects.
- Use of biopesticides and botanicals.
- Conservation of natural enemies.
- Targeted pesticide application based on ETLs.
- Contribution of Beneficial Insects to Rabi Crop Production

1. Increased Pollination and Yield

- Mustard yields increase by 30–70% with active bee pollination.
- Fennel, coriander, carrot seed crops require pollinator support to achieve economic yield.
- Pulse crops like chickpea benefit from solitary bees.

2. Natural Suppression of Key Pests

- Ladybirds and parasitoids control aphid outbreaks in mustard and wheat.
- Chrysoperla larvae keep leaf miner and soft pests suppressed in peas and leafy vegetables.
- Ground beetles reduce soil pest populations.

3. Reduced Pesticide Use

- Healthy populations of natural enemies reduce the need for chemical insecticides, lowering production cost and residue levels.

4. Enhanced Soil Fertility

- Decomposer insects improve soil aeration, organic matter breakdown, and nutrient recycling.

Conclusion
Beneficial insects form the backbone of ecological agriculture, supporting both productivity and sustainability. In Rabi season fields, these insects are essential for pollination, natural pest regulation, and ecosystem balance. Pollinators ensure higher seed set and yield in mustard, coriander, and many vegetables, while predators and parasitoids keep destructive pests under control. Soil-dwelling beneficials improve fertility and crop establishment. Conservation measures such as habitat management, use of botanicals, selective pesticides, and integrated pest management play a crucial role in protecting beneficial insect populations. Recognizing and harnessing the services of beneficial insects can significantly enhance crop productivity, reduce production costs, and promote environmental health. A shift toward biodiversity-centered crop management is vital for sustainable Rabi season agriculture.

Future Prospects
The future of beneficial insect conservation lies in:

1. Ecological Engineering : Designing cropping systems with flowering strips, trap crops, and diversified landscapes.

2. Advanced Biocontrol Technologies : Use of improved strains of Trichogramma, predatory mites, and combined microbial bioagents.
3. Precision Conservation Tools : AI-based monitoring, drone scouting, and automated identification of insects.
4. Climate-Smart Pest and Pollinator Forecasting : Predictive models that forecast beneficial insect activity based on climate data.
5. Breeding for Attractive Crop Varieties : Developing crop cultivars that produce nectar, pollen, or volatiles that attract beneficial insects.
6. Policy Support : Subsidies for beekeeping, organic farming, and IPM will encourage farmers to adopt conservation practices.

With scientific advancements and ecological awareness, beneficial insects will increasingly shape sustainable field crop production in the Rabi season.

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WHY DO GREEN GRAM LEAVES TURN YELLOW? HIDDEN CAUSES EVERY FARMER SHOULD KNOW

Sayani Das

Department of Agronomy, Faculty of Agriculture,
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur-741252, Nadia, West Bengal, India
*Corresponding Email: sayani9916@gmail.com

Introduction

Leaf yellowing in greengram (*Vigna radiata*) is a common problem for farmers, but the cause is to some extent misdiagnosed as a singular disease issue. There are multifactorial reasons for yellowing of leaf including lack of nutrient availability (N, Fe, S etc.), decline in soil health, poor drainage, waterlogging, moisture stress, and attacks by pests and diseases. Among these, yellow mosaic virus (YMV) is most severe, which is transmitted by whiteflies. Yellowing usually reduces photosynthetic pigments, reduces plant vigour, limits pod-setting, and reduces greengram yield (Kumar et al., 2012). This article explains why yellowing of greengram leaf occurs, so farmers can easily recognize the symptoms, find the real cause and avoid spraying pesticides unnecessarily.

Reasons for greengram leaf yellowing

1. Viral disease (YMV):

Yellow Mosaic Virus is recognized as the most destructive source of yellowing in greengram leaves. It causes bright, irregular yellow patches that later become a yellow mosaic that covers the whole leaf, causing leaf crinkling and brittleness. The plants remain short, with little flowering or pod development. The disease is vectored rapidly by whitefly in the population especially in warm, humid weather and common with many varieties in vegetation.

2. Nutrient deficiency

Nitrogen deficiency:

Nitrogen is a key ingredient of chlorophyll, the pigment that gives leaves their green colour. When greengram suffers from nitrogen deficiency, chlorophyll production decreases and leaves develop yellowing that begins from the older and lower leaves. This occurs because nitrogen is highly mobile and the plant shifts available nitrogen from older to younger tissues. The plant becomes stunted with less branching, thinner stems and a limited leaf area while growth and productivity decrease sharply. Some common triggers of low nitrogen in soils tends to be low organic matter in the soil, low nitrogen fertilizer application, or water-logging which restricts nitrogen uptake.

Potassium deficiency

Potassium is important for enzyme activation, stomatal function and translocation of sugars from the leaves. When greengram is deficient in potassium, symptoms include yellowing that starts at the leaf margins and moves into the leaf, followed by brown scorching or necrotic patches. The plants exhibit weak stems and lodging and the pods are small with shrivelled grain inside. Potassium deficiency is common in intensively cropped soils that have never received K fertilization.

Magnesium deficiency

Magnesium is the central atom in the chlorophyll molecule. When greengram is deficient in magnesium, symptoms include interveinal yellowing which will start on the older leaves first, because magnesium is mobile and can be translocated to younger parts of the plant. The leaf lamina turns a dull yellow and the veins are still green. Long-term magnesium deficiency will weaken photosynthesis and lead to defoliation, fewer flowers and poor grain filling.

Sulphur deficiency

Sulphur deficiency results in light yellow leaves mostly on the young upper foliage because sulphur is immobile in the plant. Leaves tend to be small, narrow and pale. Sulphur regulates root-nodulation because both protein and enzymes rely on sulphur for synthesis and are especially important in legumes. Deficiency is often apparent in sandy soils, zones with low organic carbon and even fields grown continuously on fertilizers that do not contain sulphur; Compounding the yellowing and reduction in vegetative vigour is the reduced uptake of nitrogen as nitrogen fixation is reduced from sulphur deficiency.

Iron deficiency

Iron is important in the synthesis of chlorophyll and electron transport. Deficiency symptoms in greengram include interveinal chlorosis in which the veins stay green while the space between the veins turns yellow on leaves that have just emerged. In extreme cases leaves are almost white and growth is markedly slow. Iron deficiency is commonly associated with calcareous, alkaline soils and excessive phosphorus application.

Zinc deficiency

Zinc is involved in auxin synthesis and metabolic activities. Zinc deficiency is characterized visually by yellowing greengram leaves that includes small brown spots, or discoloration and a reduced size of leaves starting with mostly the middle leaves. The greengram leaves develop a rosette appearance from short leaves. In time and when severe, zinc deficiency can lead to poor root growth, reduced flower donors with poor pollen viability and yield reductions.

Molybdenum deficiency

Molybdenum modulates nitrate reduction and biological nitrogen fixation in legumes. Without molybdenum greengram leaves are pale with mottled yellowing that happens first in middle-aged leaves. These plants show poor nodulation and nitrogen metabolism that results in generally weak stems and delayed flowering with low pod set. Soil acidity most increases risk of a molybdenum deficiency.

3. Fungal diseases

Cercospora leaf spot

Cercospora thread fungus, or brown stripe, creating small brown spots surrounded by a yellow halo on leaves. As the infection develops, the yellow area increases, while the leaves are drying out prematurely. The disease is favoured under long and humid conditions as well as with densely spaced plants. If severe enough, significant leaf drop can occur, resulting in considerable reduction in pods and yield.

Root rot and collar rot

Soil-borne fungi, such as *Rhizoctonia, Fusarium* and *Macrophomina,* infect the root system and collar region. The first symptom is sudden yellowing and drooping of leaves, starting from the top of the plant, followed by wilting. Roots are dark, rotten and brittle upon uprooting. The disease rapidly spreads in poorly drained, continuous greengram fields during hot weather.

4. Insect pest

Whitefly:

Whiteflies damage plants by feeding on the sap, resulting in general yellowing and curling of tender leaves. Whiteflies also transmit YMV (Yellow Mosaic Virus) and make the damage alone more severe. If whiteflies infest heavily, it can lead to a sticky honeydew deposit and sooty mold, drastically decreasing photosynthesis. Infestations become heavier during warmer, drier periods.

Jassid (Leafhopper)

Jassids transmit a distinct V-shaped yellowing at the leaf tip that continues along the margins, eventually browning. The edges of the leaves would be cupped, rough and brittle. The plant remains dwarf with minimal flowers and pods. The problem becomes worse during hot and dry periods, but especially for susceptible varieties.

5. Environmental and soil stress

Waterlogging / poor drainage

Excess water in soils limits root respiration and replenishment of nutrients uptake productivity which will manifest with leaves uniformly yellowing alongside drooping. Waterlogged plants will show signs of wilting during hot sunny hours or possibly die if waterlogged stress continues. They will also develop wiry weak blackened roots and reduced budding, among other negative plant health. This happens in heavy soils, flat fields without slope or continuous rains, without need for full saturation to cause the aforementioned problems.

Drought stress

Greengram loses ability to extract nutrients and maintain chlorophyll activity, leading to continued yellowing across the field, folding of leaves and reduced turgor with drought stress. The crop will typically drop flowers and young pods as soon as the water deficit is reached to conserve energy with drought stress. With prolonged or persisting drought, premature senescence will lead to slow or no branching and very low yields. Sandy soils and crops sown late are particularly subject to this syndrome.

Salinity stress

Soil and irrigation water salinity leads to an osmotic imbalance and sodium and/or chloride ion toxicity. In greengram this stress induces a distinct yellowing symptom, similar to scalding, translating into burned leaf tips and margins progressing into the inner leaf as it worsens the salinity exposure. The high levels of salts present in the soil zone near the roots prevents the plant from an uptake of water thus demonstrating physiological drought even if moisture is present. The plant becomes weak, stunted in growth and fails to properly develop pods. Salinity stress is more prevalent in coastal areas, low-lying fields or areas that have been irrigated with saline groundwater.

Soil compaction

Compacted soils displace pore spaces in addition to reducing oxygen availability to roots. In these conditions, greengram roots develop poorly and are often shallow which means the plant develops yellowing due to poor uptake of nutrients. In addition to yellowing, the plant often develops stunted growth with poor branching. Compaction often occurs due to puddling, heavy equipment on weak soils and soft soils in general resulting in poor development of flowering or pod formation.

High temperatures / heat stress
In instances of heatwaves or continuing high temperatures, greengram has increased respiration and rapid moisture loss. This results in yellowing of the leaves with excessive flower drop that greatly reduces its yield potential. Heat stress is the most damaging during flowering and early pod development, as reproductive structures are very sensitive. Sandy soils and late kharif sowings experience this more.

Cold shock in the early stage
Greengram is very sensitive at low temperatures during the early growth stage. Exposure to cold weather very soon after germination results in very light-yellow leaves and extremely stunted growth, as metabolic and photosynthetic activities are impeded. Seedlings are weak and recovery is slow even if the temperature returns to normal. Usually, early rabi sowings that are done without adequate soil temperature, or in some cases cold wet winter rain situations cause this event.

6. Nodulation / rhizobium failure
Greengram relies on symbiotic Rhizobium bacteria to fix biological nitrogen. When nodulation is limited, or absent, the plants show yellowing just like nitrogen deficiency, especially from lower leaves. No nodulation may result from acidic or saline soils, no seed inoculation, high amounts of nitrogen fertilizer at sowing, or ineffective native Rhizobium strains. The plants remain weak, have little branching and flower at a delayed time because there is lack of nitrogen due to nodulation failure.

7. Chemical injuries
Inappropriate or excessive chemical application can directly harm greengram foliage and roots. Herbicide injury results in rapid yellowing (shortly after application) along with twisting or deformities of leaves with drift or overdose. Excessive use of fertilizers, in particular permutations with ammonium, can result in tip burn, yellowing and lastly tissue necrosis. Residual soil herbicides from previous crops can lead to patchy yellowing in the field with the strongest yellowing collecting where residues have accumulated (gift of a previous crop). Often these injuries can lead to compromised growth and variability (size and color) of crop stand.

8. Crop management problems
Some agronomic practices can inadvertently contribute to yellowing. Plant crowding will increase competition for nutrients, sunlight and moisture, which can lead to pale yellow, weak, spindly plants. Sowing too deeply can result in delayed emergence and weaker precocious seedlings with yellow cotyledon leaves as the plant drains food reserves before emergence. Taller intercrops can shade the crop and restrict photosynthesis, leading to the yellowing lower or shaded leaves often compromised flowering or pod setting. Appropriate sowing depth, spacing and crop geometry will be important to keep greengram green.

Table 1: Quick diagnosis guide for farmers

Symptom	Possible Cause
Mosaic yellow patches on young leaves	Yellow Mosaic Virus
Yellowing with insects on leaves	Whitefly/jassid/thrips
Yellowing starting from old leaves	Nitrogen / Magnesium deficiency
Yellowing starting from young leaves	Sulphur / Iron deficiency

Symptom	Possible Cause
Pale leaves with wilting	Waterlogging / drought
Uniform yellowing with weak roots	Nodulation failure
Sudden yellowing after spray	Chemical injury

Table 2**: Identification table for yellowing in greengram leaf**

Cause		Key field symptoms	Where yellowing starts	Extra clues / simple tests
Yellow Mosaic Virus (YMV)		Bright yellow + green mosaic patches, mottled leaves	Young leaves first	Look for whiteflies on underside of leaves. Mosaic pattern does not fade when rubbed with hand.
Nutrient deficiency	**Nitrogen deficiency**	Uniform pale-yellow leaves	Older (bottom) leaves first	Spray 1% urea on small area- leaves become greener in 3–5 days-confirms N deficiency.
	Potassium deficiency	Leaf margin turns yellow-brown scorching	Middle/older leaves	Yellowing starts from leaf edge inward, not whole leaf at once.
	Magnesium deficiency	Interveinal yellowing on older leaves, veins stay green	Older leaves	Pattern similar to iron deficiency but starts from bottom leaves.
	Sulphur deficiency	Uniform yellowing, thin narrow pale leaves	Young leaves first	Stem becomes slightly purple in severe cases. Nodulation often reduces.
	Iron deficiency	Green veins + yellow area between veins (interveinal chlorosis)	Top new leaves first	Common in alkaline / waterlogged soils. Spray 0.5% $FeSO_4$ + lime - recovery in 4–6 days.
	Zinc deficiency	Yellowing with small leaves, short internodes, rosetting	Young leaves	Plant looks stunted at top though lower plant is normal.
	Molybdenum deficiency	Pale, mottled leaves; weak plants; delayed flowering	Middle leaves	Few/no nodules; occurs mainly in acidic soil; does not recover fully after nitrogen spray
Waterlogging / root rot		Yellowing + wilting, drooping	Lower leaves first	Bad smell from roots, plants easily pull out from soil.

Cause	Key field symptoms	Where yellowing starts	Extra clues / simple tests
	leaves		
Drought stress	Pale yellow leaves + drooping, leaf scorch	All leaves	Soil dry, flowers/pods drop easily.
Thrips / mites	Silvery or bronze streaks, leaf curling	Young leaves	Shake leaf on paper → tiny insects visible.
Leaf miner	Yellow serpentine tunnels/lines inside leaves	Local patches on leaf	If leaf is held against light, tunnels are clearly visible.
Herbicide toxicity	Sudden yellowing + twisted/deformed leaves	Patchy across field	Occurs soon after spray or when adjacent plot sprayed.
Salinity	Yellowing + burnt tips and margins	Lower leaves first	White salt crust may be visible on soil surface.
Poor nodulation (Rhizobium failure)	Yellowing like nitrogen deficiency	Older leaves	Uproot plant - few or no pink nodules on roots.

Conclusion

There are several causes of greengram leaf yellowing, both known and hidden - viral disease, insect pests, nutrient deficiency, improper soil moisture management, failed nodulation, chemical injury and overcrowding. There is a unique pattern of yellowing depending on the cause. Good farmers will look closely at where the yellowing is (upper or lower leaves), the shape of the leaves, presence of insects and soil condition before acting on anything. This minimizes pesticide application and saves money. With a consistent management of soil health, even crop nutrition, seed treatments, proper spacing and insect management, greengram crops can remain green, healthy, and high-yielding throughout the season.

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ASSESSING USERS' SATISFACTION WITH CASSAVA PROCESSING CENTRE VIA NIGERIAN STORED PRODUCTS RESEARCH INSTITUTE (NSPRI) ADOPTED VILLAGES SCHEME IN ISALE AWE, KWARA STATE, NIGERIA

Patrick Kayode Orimafo[1], Ismail Oladeji Oladosu[2], David Ahmed Adamu1, and Chinwendu Vivian Ohaeri[1]

[1]Research Outreach Department, Nigerian Stored Products Research Institute Ilorin, Kwara State, Nigeria
[2]Ladoke Akintola University of Technology, Ogbomoso. Oyo State, Nigeria
*Corresponding Email: pat4knight@gmail.com

Abstract

The study assessed users' satisfaction with cassava processing centre via Nigerian Stored Products Research Institute (NSPRI) Adopted Villages Scheme in Isale Awe, Kwara State, Nigeria. The population of the study includes all the agro-processors in the study area. A multistage sampling procedure was employed to select 48 respondents (cassava processors) for the study. The primary data obtained with the aid of a well-structured questionnaire were analyzed using descriptive and inferential statistics (Linear Regression model). The mean age of the respondents stood at 48.75±12.535 years, majority of the respondents were male (83.3%) with a mean households size of 9.08±4.471 and educated (66.7%). Cassava processing centre provided by NSPRI was widely utilized (weighted mean score (WMS) of 2.58) by cassava processors in Isale Awe. Most of the respondents were more satisfied with the accessibility of the technology (WMS = 3.92). Moreover, 50.0 percent of the respondents were satisfied with NSPRI cassava processing centre on high level. High cost of maintenance (WMS = 2.17) remains the major challenge facing the utilization of cassava processing centre in the study area. The result of linear regression model indicated that age (t = 2.907***) and educational level (t = 3.404***) were significantly related with the level of satisfaction of NSPRI technology. Since educational level is an important determinant of users' satisfaction with cassava processing centre provided by NSPRI, there is adequate need for advocacy for acquisition of quality education to further enhance effective utilization of technology with attending better output and higher return to investment.

Keywords: Postharvest technologies*, Agro-processors, Satisfaction, Adopted Villages Scheme, NSPRI, Nigeria.*

Introduction

The growing importance of cassava (*Manihot esculenta*) among crops grown in Nigeria is not only related to its increasing demand as food but also as food security (FAO, 2018). Moreover, cassava can be consumed raw but it is mostly consumed in processed forms (cassava flakes, cassava flour, and cassava paste). In fact, over eighty percent (88%) of cassava produced in Africa is used for human food, with over 50% used in the form of processed products (Westby, 1991; Oyewole and Eforuoku, 2019). Conversely, 7 in every 10 Nigerians consume, at least, a product of cassava once in a day (Njoku and Muoneke, 2008). It is a widely satisfactory energy food source to over 600 million consumers of cassava globally (FAO, 2015). Cassava processing by traditional methods is labour-intensive but the increasing application of improved processing technology has reduced processing time and labour and encouraged increased production. Although, the industrial utilization of cassava products is increasing but still accounts for less than 5% of the total production probably due to inaccessibility of small holder agro-processors to improved technologies emanating from the National Agricultural Research Institutes (NARIs) (Shittu *et al*., 2016). This shows there is more to be desired in the nation's cassava processing sub-sector especially in respect to utilization of improved postharvest technologies.

In order to facilitate the dissemination of improved technologies to small holder agro-processors, the "Adopted Villages Scheme" was introduced to the National Agricultural Research Institutes (NARIs) in Nigeria and the Agricultural Research Council of Nigeria in 1996 under the World Bank Assisted Programme of National Agricultural Research Project (NARP) (ARCN, 2008). Each Institute/College of Agriculture is expected to identify two communities/schools not more than twenty kilometers away from its official location within their mandate areas. Furthermore, the institute will select farmers where the farms or fields will be used as 'show room' for the communities of the impact of the technologies they are promoting. The selected communities are to help in the early evaluation and dissemination of the technologies generated by a particular research institute in its mandate crops (IAR&T, 2009).

In line with the directive, Nigerian Stored Products Research Institute (NSPRI) identified and established the "Adopted Villages Scheme" in Isale Awe community in Asa Local Government Area (LGA), Kwara State, Nigeria as a new approach in the dissemination of improved postharvest technologies to end users. The objectives of establishment and management of the adopted villages are: provision of opportunity for community entry and confidence building; facilitation activities; training and empowerment activities; development activities; promotional and extension activities; and establishment and management of outreach centres/secondary schools.

However, since the establishment of the adopted villages scheme in Asa Local Government Area of Kwara State, there has not been any empirical study into the users' satisfaction with the available postharvest technology in the area. This study was therefore designed to provide empirical information on the users' satisfaction with cassava processing centre via NSPRI Adopted Villages Scheme in Isale Awe community, Kwara State, Nigeria.

Literature Review

Technology/innovation Transfer

Technology transfer plays a vital role in driving innovation by accelerating the commercialization process, bridging the gap between academia and industry, facilitating cross-sector collaboration, and providing resources and support for startups. By understanding the importance of technology transfer and implementing effective strategies, organizations can unlock the full potential of their innovative ideas and contribute to societal progress. Innovativeness is a tendency to be a technology pioneer and thought leader. Innovativeness measures the extent to which an individual believes he or she is at the forefront of trying out new technology-based products and/or services (Demirci and Ersoy, 2020). Technology readiness explains the possibility of someone appreciating and applying new technologies. At the same time, innovation defined in the product development literature is one's willingness to adopt new products (Ricardo and Bianca, 2019). Therefore, regarding technology adoption, we expect that individuals with a high degree of innate innovativeness (i.e., openness to new things) shows inherent interest in trying new technologies and become innovators or early adopters (Blut and Wang, 2019).

Innovativeness is related to people's inclination to explore and try new things (Parasuraman and Colby, 2001). Innovative people prefer to explore their world which makes them more open to accepting new technology. Another key aspect of innovativeness is the tendency for people to collect and share information. Innovative individuals prefer learning new things and developing as they would then tell other people what they have learned. In general, innovative consumers play an important role in giving advice to other consumers (Parasuraman and Colby, 2001). People with high innovativeness traits have been described as those who possess powerful inherent inspiration when it comes to the use of new technology as they cherish the excitement of trying the innovation (San-Martín, 2018). Gaitan (2019) added that the innovativeness trait represents the degree that which individuals want to try and use new technology services and products to become thought leaders on technology-related issues. In particular, these innovative people are also found to be very intrigued by new technologies in general and in exploring their attributes.

Customer Satisfaction

Customer Satisfaction has been a critical term in business that has received extensive attention among researchers and practitioners. Customer Satisfaction has gained centrality in marketing literature because of its importance as a key component of business strategy and an aim for business activities, especially in today's competitive market. Customer satisfaction has a positive effect on an organization's profitability (Gunasundari and Kulkarni, 2022). The more customers are satisfied with produces or services accessible, the more are chances for any successful business as customer satisfaction leads to repeat purchase, brand loyalty, and positive word of mouth marketing (Rajathi and Siva, 2018). Customer satisfaction leads to repeat purchases, loyalty and to customer retention (Gunasundari and Kulkarni, 2022).

Hadiyati (2019) has further defined satisfaction as a feeling of pleasure or disappointment of a person, resulting from comparing a product or service noticed performance (or result) towards his or her expectations? Satisfaction is the customers or clients experience that have experienced or received contact with the organization. Satisfaction on the other hand, is about the specific experience customers who have received various stages of service (Humayon *et al.*, 2018). It means that customers have high expectations of the role of the employees of an organization especially, for the front-line staff; therefore, the successful meeting of customer expectations will reflect their satisfaction. Today most successful companies have taken the strategy of raising expectations and delivering performance to match. Such companies track their customers‟ expectations, perceived company presentation, and customer satisfaction. Highly satisfied customers produce several benefits for the company. Satisfied customers remain connected for a longer period and talk favourably to others about the company and its products and services.

Methodology

Study Area: The study was conducted in Isale Awe Village in Asa Local Government Area of Kwara State. The study area is located at an elevation of 267 meters above sea level and its population amounts to 142,275 in National Population Census (NPC) (2006). Its coordinates are 8º37'0'N and 4º22'60'E in DMS (Degrees Minutes Seconds) or 8.61667 and 4.38333 (in decimal degrees). The area is characterized by two distinct seasons, namely the wet and the dry seasons. The annual rainfall received in this region is very moderately high, usually above 1,800 mm. Temperatures are fairly uniform throughout the year and the differences between day and night are slight. Isale Awe stands as "a thriving agricultural hub" in Kwara State with a rich farmlands and bustling trade. It serves as a vital marketplace where farmers and traders converge on market days. The major crops in Isale Awe are vegetables, yam, cassava and maize. The study area is dominated mainly by Yoruba people. Isale Awe Village is within a 20 km radius from the Kwara State capital, Ilorin (LCRI, 2009). The village is within the mandate area of NSPRI and is also into mass production of the mandate commodity of the research institute, this qualifies her to be one of the adopted villages of NSPRI in line with the directive of the Agricultural Research Council of Nigeria (ARCN, 2008).

Population of the study: the population of the study include all the agro-processors in the study area.

Sampling procedure and sample size: A multistage sampling procedure was employed to select 48 respondents for the study. The first stage involved purposive selection of Isale Awe community since is one of the adopted villages in Asa Local Government Area of Kwara State and well known for cassava processing while the second stage involved the random selection of four (4) cells out of the eight (8) cells in Isale Awe community. The third stage involved the random selection of twelve (12) cassava processors from each of the selected cells in the community to give a total number of forty eight (48) respondents as the sample frame for the study.

Source and type of data: Primary data were used for this study. The primary data were obtained with the aid of a well-structured questionnaire and unstructured interview guide.

Data analysis: The data collected were analyzed using descriptive statistics and inferential statistics (Pearson's Product Moment Correlation model).

Measurement of variables: The level of satisfaction with cassava processing technology provided by NSPRI were obtained using a 5-point Likert scale namely; Outstanding (5); Exceed Expectation (4); Meet Expectation (3); Below Expectation (2) and Need Improvement (1) strongly agree = 5, agree = 4, undecided = 3, disagree = 4, and strongly disagree = 1. The benchmark was obtained by adding 5+4+ 3+2+1 = 15 which is divided by 5 to give 3.0. Any mean score of 3.0 and above is favorable, otherwise not favourable (Author defined). The challenges in the utilization of cassava processing technology were obtained using a 4-point scale namely; Very Severe (3), Severe (2), Moderately Severe (1) and Not Severe (0)

Results and Discussion

Socio-Economic Characteristics of the respondents at Isale Awe community

Table 1 presents the socio-economic characteristics of the cassava processors. The results in Table 1 showed that 41.7 percent of the respondents were between 41-50 years of age, 33.3 percent of the respondents were above 50 years of age, 16.71 percent of the were between 31-40 years of age while only 8.3 percent of the respondents were within 30 years of age. The mean age of the respondents stood at 48.75±12.535 years. This implies that the respondents are still in their economically active age and can adequately engage in cassava processing activities. Similarly, the mean age in this research work is higher than the mean ages of 43 and 42 years recorded in Kwara State and Kogi State respectively as reported by Adedoyin *et al*. (2025).

The results in Table 1 showed that majority (83.3%) of the respondents were male while only few (16.7%) were female. This finding indicated that cassava processing is a male dominated business in the study area. This finding negates the general assumptions from the previous studies of Ikwu-Oche *et al*. (2024) who reported that cassava processing industry is dominated by married women. Table 1 indicated that 64.3 percent of the respondents had between 6-10 members in their households, 28.6 percent of the respondents had more than 10 members in their households while only 7.1 percent of the respondents had between 1-5 members in their households. Moreover, the average member of the households was found to be 9.08±4.471 indicating a very large household size. This large household size could be utilized to carry out cassava processing thereby reducing the cost of labour. This is in agreement with the views of Adeniyi *et al*. (2023) who reported that having large to medium household size is favourable as members would be used as source of labour thus reducing labour cost and increasing processing capacity of the household.

Table 1 showed the distribution of respondents by educational level. It was indicated that 33.3 percent of the respondents had no formal education. However, 41.7 percent of the respondents had primary school education, 8.3percent of the respondents had secondary education, 0.0 percent of the respondents had tertiary school education while 16.7 percent of the respondents had non-formal education. The finding vividly connotes the fact that most of the respondents were educated which could be an important determinant of customer satisfaction with the technology.

Table 1: Distribution of respondents by Socio-Economic Characteristics

Socio-Economic Characteristics	Frequency	Percentage
Age range (Years)		
≤30	4	8.3
31-40	8	16.7
41-50	20	41.7
Above 50	16	33.3
Total	48(100.0)	100.0
Mean	48.75	
Standard deviation	12.535	
Range	Minimum= 23 Maximum = 65	
Sex		
Male	40	83.3
Female	8	16.7
Household size		
1-5	12	25.0
6-10	24	50.0
Above 10	12	25.0
Mean	9.08	
S.D	4.471	
Educational level		
No formal education	16	33.3
Primary school	20	41.7
Secondary school	4	8.3
Tertiary school	0	0.0
Non-formal education	8	16.7

Source: Data analysis Outputs, 2025

Available NSPRI Technology in the study area

Table 2 presented the distribution of respondents based on the availability of NSPRI technology in the study area. The result in the table 5 indicated that all (100.0%) of the respondents indicated the availability of cassava processing unit/centre provided by NSPRI in their area. The finding therefore revealed that cassava processing unit established by NSPRI is readily available for use in the study area.

Table 2: Distribution of respondents by available NSPRI Technologies in the study area

NSPRI Technology	Frequency	Percentage
Cassava processing centre	48	100.0

Source: Data Analysis Outputs, 2025

Satisfaction with NSPRI Technology at Isale Awe

Table 3 presented the distribution of respondents by the level of satisfaction with NSPRI Technology (cassava processing centre) at Isale Awe community. The result in the Table 3 indicated that most of the respondents were more satisfied with the accessibility of the technology with a weighted mean score (WMS) of 3.92. Others in the rank order of satisfaction include quality of products (colour, taste and odour) (WMS = 3.83), timeliness of action/result/output (WMS = 3.83), location of the technologies (WMS = 3.08), ease of use (operational design) (WMS = 3.08), capacity (WMS = 2.58), technology status/condition (WMS = 2.25), safety of products (WMS = 2.25) and organizational supports (WMS = 1.75). This finding implies that accessibility of the technology is a good determinant of the level of satisfaction with NSPRI technology in the study area. In order to test the adequacy of any technology in meeting the aspirations of the end users, it must be readily accessible. Meanwhile, this satisfaction for the provided services can be measured by the consumers' feedback. Customer service provided by this technology can either be or both tangible and intangible which implies that end users need to see, feel, or even test run the technology to proof its ability in meeting their expectations. So, satisfaction or dissatisfaction occurs when the customer evaluates expectations with the performance or results received. Therefore, a technology is considered to be satisfying when it fulfills their needs and expectations (Hadiyati, 2019). In that respect, service providers offer products or services that match a customer's expectations and hope to satisfy the customer and pay attention to them with their excellent customer services (Rajathi and Siva, 2018). The higher the satisfaction or attention, the more guaranteed the customer loyalty (Cheung and Lee, 2005). In line with current finding, Dewi Sanjaya and Martono (2012) identified service quality as the major factor that determines customer's satisfaction with a given technology.

Table 3: Distribution of respondents by level of satisfaction with NSPRI Technology at Isale Awe

NSPRI Technologies	O	EE	ME	BE	NI	WMS	Rank
Quality of products (color taste odor)	20(41.7)	8(16.7)	16(33.3)	0(0.0)	4(8.3)	3.83	2nd
Accessibility	20(41.7)	8(16.7)	16(33.3)	4(8.3)	0(0.0)	3.92	1st
Timeliness of action/result/output	20(41.7)	4(8.3)	20(41.7)	4(8.3)	0(0.0)	3.83	2nd
Capacity	8(16.7)	4(8.3)	12(25.0)	8(16.7)	16(33.3)	2.58	6th
Location	8(16.7)	8(16.7)	20(41.7)	4(8.3)	8(16.7)	3.08	4th

NSPRI Technologies	O	EE	ME	BE	NI	WMS	Rank
Technology status/condition	8(16.7)	0(0.0)	12(25.0)	4(8.3)	24(50.0)	2.25	7th
Safety of products	16(33.3)	4(8.3)	16(33.3)	0(0.0)	12(25.0)	2.25	7th
Ease of use (operational design)	16(33.3)	0(0.0)	16(33.3)	4(8.3)	12(25.0)	3.08	4th
Organizational supports	0(0.0)	4(8.3)	8(16.7)	8(16.7)	28(58.3)	1.75	9th

O = Outstanding (5); EE = Exceed Expectation (4); ME = Meet Expectation (3); BE = Below Expectation (2); NI = Need Improvement (1)

Source: Data Analysis Outputs, 2025

Categorization of level of satisfaction with NSPRI Technology at Isale Awe

Table 4 presented the distribution of respondents by categorization of level of satisfaction with NSPRI Technology at Isale Awe community. The result in the Table 4 indicated that 50.0 percent of the respondents were satisfied with NSPRI cassava centre on high level, about 41.7 percent of the respondents were satisfied with NSPRI cassava centre on moderate level while a few (8.3%) of them were satisfied with NSPRI cassava centre on low level. From the result of the finding, it was observed that cassava centre at Isale Awe recorded high satisfaction rate among the cassava processors indicating the fact that this innovation had contributed immensely to cassava processing in the study area. This feeling of satisfaction with this technology will more likely engender high level of loyalty to Nigerian Stored Products Research Institute's technological transfer agenda. In line with this assumption, other authors (Foroudi *et al*., 2018) reiterated that loyal customers (end users) are likely to share positive news about the technology that meets their expectations especially through word of mouth and on social media. This implies that customer satisfaction is important for companies to gain the trust of consumers, and make them continue to use their services (Merek, 2018). This can be established by offering good and competitive services that are well received in the society (Susanti, 2018; Nurlia, 2019).

Table 4: Distribution of respondents by categorization of level of satisfaction with NSPRI Technology at Isale Awe

NSPRI Technology	Categorization of satisfaction with NSPRI Technology		
	High	Medium	**Low**
Cassava processing centre	24(50.0)	20(41.7)	4(8.3)

Mean = 27.67; Standard Deviation: 8.120

Source: Data Analysis Outputs, 2025

Challenges faced in the utilization of NSPRI Technology

Table 5 presented the distribution of respondents by challenges faced in the utilization of NSPRI Technology at Isale Awe community. The challenges faced in the utilization of NSPRI Technology at Isale Awe community in the rank order include high cost of maintenance (WMS = 2.17), high cost of technology (WMS = 1.67), poor coordination (WMS = 1.43), limited capacity (WMS = 1.25), poor collaboration (WMS = 1.17), lack of training (WMS = 1.08), technical know-how (WMS = 0.67) and inadequate access to technology (WMS = 0.42). From the result of the finding, it was observed that the effects of the challenges faced in the utilization of NSPRI Technology among the cassava processors at Isale Awe community was below average indicating that the challenges were not significant enough to undermine the contribution of NSPRI technology to overall development in cassava processing in the study area. However, high price of any technology can affect the level of patronage of the technology thereby undermining the expected coverage of the technology. Similarly, previous studies (Dewi Sanjaya and Martono, 2012) showed that the price tag is one of the determinants of customer satisfaction. Therefore, to fulfill customer satisfaction, companies need to provide affordable prices and good quality services (Roring, Oroh, and Gulla, 2015). Many studies have analyzed the influence of price on customers' satisfaction (Natasja Hosang, Tumbel, and Moniharapon, 2016).

Table 5: Distribution of respondents by challenges faced in the utilization of NSPRI Technology

Challenges	VS	S	MS	NS	WMS	Rank
Technical know-how	4(8.3)	0(0.0)	20(41.7)	24(50.0)	0.67	7th
Limited capacity	4(8.3)	12(25.0)	24(50.0)	8(16.7)	1.25	4th
Poor collaboration	4(8.3)	16(33.3)	12(25.0)	16(33.3)	1.17	5th
Poor coordination	8(16.7)	16(33.3)	12(25.0)	12(25.0)	1.43	3rd
High cost of technology	12(25.0)	16(33.3)	12(25.0)	8(16.7)	1.67	2nd
Inadequate access to technology	0(0.0)	0(0.0)	20(41.7)	28(58.3)	0.42	8th
High cost of maintenance	28(58.3)	4(8.3)	12(25.0)	4(8.3)	2.17	1st
Lack of training	12(25.0)	0(0.0)	16(33.3)	20(41.7)	1.08	6th

VS = Very Severe (3), S = Severe (2), MS = Moderately Severe (1), NS = Not Severe (0)
Mean = 9.83; S.D = 4.610

Source: Data Analysis Outputs, 2025

Hypothesis

Influence of selected Socio-economic characteristics and level of satisfaction with NSPRI Technology in Isale Awe community

Table 6 presented the result of linear regression model showing the relationship between selected socio-economic characteristics and level of satisfaction with NSPRI technology in Isale Awe community. It was revealed that age (t = 2.907***) and educational level (t = 3.404***) were significantly related with the level of satisfaction of NSPRI technology. The relationship was significant at 5% level indicating the fact that household size and educational level are strong determinants of the level of satisfaction with the usage of a technology. Surely, a year increase in the years of education of the household head will lead to 30.5 percent increase in the likelihood of a household's satisfaction with usage of cassava processing technology provided by NSPRI being in Isale Awe. This is because educated individuals will be able to adopt new technologies that have potential to reduce stress and capable of boosting their production level. In fact, a unit increase in age of individuals will result in 2.91 percent increase in the likelihood of the household being food insecure. Honestly, education standing and age seems to guarantee better insight through adequate analysis, exposure and acquisition of requisite knowledge about diverse issues. So, education and age help in determining individual's needs and expectations hence, determinants of satisfaction. For instance, quality assessment starts from their needs and ends on their perception. Invariably, there is high propensity of satisfaction when the needs and expectations are guaranteed.

Table 6: Relationship between selected Socio-economic characteristics and level of satisfaction with NSPRI Technology

Variables	B-Value	Standard Error	t-value	p-value
Constant	16.911	5.388	3.139	0.003
Age	0.291	0.100	2.907***	0.006
Household size	0.381	0.245	1.557	0.127
Educational Level	3.053	0.897	3.404***	0.001

R = 0.515; R2 = 0.266; Adj.R2 = 0.216; Std. Error of the Estimate = 7.191; F-statistics = 5.306
*****Significant at 1% level**

Source: Data Analysis Outputs, 2025

Influence of challenges faced in the utilization of NSPRI technology and level of satisfaction with NSPRI Technology in Isale Awe community

Table 7 presented the result of linear regression model showing the relationship between challenges faced in the utilization of NSPRI technology and level of satisfaction with NSPRI Technology.in Isale Awe community. It was revealed that challenges index (t = -2.855***) was significantly related with the level of satisfaction of NSPRI technology. The relationship was inversely related but significant at 1% level indicating the fact that challenges faced with the utilization of NSPRI technology is a strong determinant of the level of satisfaction with the usage of technology. In fact, challenges faced in the utilization of NSPRI technology had a 32.24 percent chance of increasing the level of satisfaction with NSPRI Technology.in Isale Awe community.

Table 7: Relationship between challenges faced in the utilization of NSPRI technology and level of satisfaction with NSPRI Technology

Variables	B-Value	Standard Error	t-value	p-value
Constant	3.979	2.919	1.363	0.180
Challenges index	0.3224	0.078	-2.855***	0.006

*****Significant at 1% level**
R = 0.392; R2 = 0.154; Adj.R2 = 0.116; Std. Error of the Estimate = 4.333; F-statistic = 4.097

Source: Data Analysis Outputs, 2025

Conclusion and Recommendations

The beneficiaries were highly satisfied with the cassava processing centre provided via Nigerian Stored Products Research Institute Adopted Villages Scheme' in Isale Awe community in Asa Local Government Area of Kwara State. This was because the technology was delivered without cost and readily accessible by the end users thereby fulfilling their needs and expectations.

On the bases of the findings of the study, the following recommendations are proffered:

a. Provision for loan disbursement should be made under the scheme so as to empower the beneficiaries to adopt and disseminate improved technologies in the study area;
b. Basic inputs should be made adequate and at subsidised rates to enable beneficiaries to take advantage of technology complimentarily since most agricultural-based technologies are multicomponent packages;

c. The scheme should work with women groups as part of the guidelines given by ARCN in order to ensure family empowerment;
d. NSPRI must see to it that the technologies developed are not only economically viable, technologically feasible, socially acceptable, ecologically adaptable but also culturally compatible to the existing agricultural practices of the end users.

Conflict of interests
The authors have not declared any conflict of interests.

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Declarations
Author contribution statement
Patrick K Orimafo: Conceived and designed the research work; Analyzed and interpreted the data.
David Ahmed Adamu, Ismail Oladeji Oladosu: Contributed analysis tools or data; gave technical insights of the paper.
Others: Analyzed and interpreted the data.

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NANOFERTILIZERS IN AGRICULTURAL SUSTAINABILITY UNDER CLIMATE UNCERTAINTY

K. N. Tiwari[1]* and Yogendra Kumar[2]

[1]Former Director, International Plant Nutrition Institute, India Program, Kanpur
[2]Marketing Director, IFFCO, Saket, New Delhi
*Corresponding Email: kashinathtiwari730@gmail.com

Abstract

Agriculture sustains nearly half of India's population and contributes about 18% to the GDP, yet it faces growing pressure from rising temperatures, erratic rainfall, droughts, and extreme weather. This paper explores pathways to sustainable farming under increasing climate uncertainty, with a focus on India. It examines scientific, technological, ecological, and policy approaches central to climate-resilient agriculture, including soil health restoration, water conservation, integrated nutrient management, crop diversification, and the use of digital tools. The study also highlights the importance of institutional reforms, coherent policies, and community participation in strengthening long-term resilience. Drawing on insights from FAO, ICAR, IPCC, and NITI Aayog, it provides a comprehensive roadmap for adopting sustainable practices that can safeguard food production, nutrition, and rural livelihoods for future generations.

Keywords: Sustainable agriculture, climate uncertainty, resilience, adaptation, India

Introduction

Agricultural productivity is increasingly threatened by climate change, with rising temperatures, irregular rainfall patterns, increased frequency of droughts, and soil degradation contributing to productivity declines and food insecurity (Goyal *et al*., 2025). Conventional fertilizers, critical for high yields, face limitations due to inefficiencies that cause nutrient losses and environmental contamination such as runoff, leaching, and emission of greenhouse gases (Mejias *et al*., 2021). As a result, sustainable, climate-resilient agricultural practices demand innovations that optimize nutrient delivery and minimize environmental harm. Nanofertilizers, leveraging nanotechnology principles, represent a pivotal advancement in this context. Their minute particle size and engineered properties enable improved nutrient bioavailability, controlled release, and enhanced interactions at the plant-soil interface (Nongbet *et al*., 2022). This empowers precision nutrition management tailored to plant demands and environmental conditions, making nanofertilizers promising tools to balance productivity with sustainability in the climate uncertainty era.

Enhanced Nutrient Use Efficiency and Delivery

Nutrient use efficiency (NUE) is pivotal in modern agriculture to maximize crop yields while preserving environmental integrity. Conventional fertilizers often suffer from poor NUE due to losses by leaching, volatilization, and fixation, which result in economic inefficiency and environmental pollution (Mejias *et al*., 2021). Nanofertilizers, nanoscale formulations designed for targeted and controlled nutrient delivery, have emerged as innovative solutions to improve NUE by synchronizing nutrient release with crop demand and minimizing losses to the environment (Goyal *et al*., 2025; Yadav *et al*., 2023).

Mechanisms Underlying Enhanced Nutrient Use Efficiency

Nanofertilizers enhance NUE via several mechanisms:

- **Controlled and Sustained Nutrient Release:** Nanofertilizers often employ nano-encapsulation or coatings that enable slow and controlled nutrient release, aligning nutrient availability with plant growth stages. For instance, urea encapsulated in hydroxyapatite nanoparticles releases nitrogen slowly over several weeks, significantly reducing losses through volatilization and leaching while maintaining crop nutrient supply (Maaz *et al*., 2025; Mejias *et al*., 2021). Similarly, nano-phosphorus fertilizers embedded in mesoporous carriers limit phosphorus fixation in soils, improving plant accessibility (Yadav *et al*., 2023).
- **Increased Nutrient Solubility and Mobility:** Nanoparticles possess large specific surface areas and enhanced reactivity, improving nutrient solubility. This facilitates greater diffusion to root surfaces and interaction with plant transporters (Kumar *et al*., 2020). For example, nano-zinc oxide formulations increase zinc solubility in soil solutions, enhancing uptake efficiency compared to conventional zinc salts (Kale & Gawade, 2021).
- **Improved Uptake Through Root and Foliar Pathways:** Due to their small particle size and surface properties, nanoparticles penetrate root epidermal layers and stomata more effectively than bulk fertilizers (Nongbet *et al*., 2022). Foliar application of nanoformulated nutrients like nano-urea and nano-zinc increases direct absorption, circumventing soil fixation and enhancing plant nutrient status especially under nutrient-limited soils (Kale & Gawade, 2021; Mim *et al*., 2025).
- **Stimulation of Root Growth and Microbial Interactions:** Nanofertilizers promote root proliferation and rhizospheric microbial activity essential for nutrient solubilization and cycling (Mim *et al*., 2025). Enhanced root surface area increases exploration capacity, improving nutrient acquisition. Simultaneously, nano-enabled micronutrient supply sustains beneficial microbial communities, indirectly boosting nutrient availability (Nongbet *et al*., 2022).

Yield Enhancement Through Improved Nutrient Use Efficiency: Nanofertilizers increase crop yields by providing nutrients in forms and timings closely aligned with plant demand, thereby minimizing nutrient stress and maximizing uptake efficiency (Yadav *et al*., 2023). Controlled-release nano formulations slow the dissolution of nutrients, maintaining optimal soil nutrient levels throughout critical growth phases.

Wheat yield improvements between 20% and 55% have been widely documented using nano-urea, nano-NPK, and nano-DAP applications compared to conventional fertilizers (Goyal *et al*., 2025; Rajput *et al*., 2023). Enhanced spike development, increased tillering, and better grain filling associated with steady nitrogen supply underpin these gains.

Similarly, rice crops experience 20% to 40% higher yields with nano-formulated nitrogen and zinc, through improved panicle number and grain filling (Kale & Gawade, 2021; Mejias *et al*., 2021). The sustained phosphorus availability contributed by nanophosphate formulations reduces nutrient limitation during critical reproductive stages.

Maize biomass and grain yields are bolstered by 20-40% through combined nano-nitrogen and nano-zinc treatments, which enhance kernel size, cob length, and nutrient assimilation efficiency

(Nongbet *et al*., 2022; Rajput *et al*., 2023). Foliar nano-sprays timed to key developmental stages improve nutrient translocation and stress resilience.

Vegetables and tuber crops such as potato also benefit, showing 25-40% yield increases linked to nano-NPK applications that enhance nutrient availability and reduce chemical input needs (Rajput *et al*., 2023).

Crop Quality Improvements Enabled by Nanofertilizers: Improved yield must be complemented by quality enhancements to ensure nutritional and market value. Nanofertilizers enhance crop quality by:

- Micronutrient Enrichment: Nano-zinc and nano-iron applications raise grain and fruit micronutrient concentrations by 20-30%, addressing 'hidden hunger' micronutrient deficiencies in human populations (Kale & Gawade, 2021; Yadav *et al*., 2023). Biofortified staple crops with higher zinc and iron content improve nutritional security.
- Protein Content Enhancement: Sustained and optimized nitrogen supply through nanofertilizers enables increased protein synthesis during grain development. In wheat and maize, protein content rises by 10-15%, improving food quality (Gopinath *et al*., 2025; Mejias *et al*., 2021).
- Antioxidant and Functional Metabolite Augmentation: Nanofertilizer treatments increase antioxidant enzymes and phenolic compounds contributing to stress tolerance, shelf-life extension, and enhanced sensory qualities in fruits and vegetables (Nongbet *et al*., 2022).
- Physical Quality Attributes: Increased grain size, weight, improved tuber shape and firmness, and better color and aroma in vegetables result from optimized nano-nutrient delivery and plant metabolic health (Rajput *et al*., 2023).

Application Strategies and Timing for Maximal Benefit: Nanofertilizers can be applied via soil incorporation, foliar sprays, seed soaking, or fertigation, with each method influencing efficacy. Foliar nano-urea sprays during tillering and panicle initiation stage maximize nitrogen uptake particularly under water-stressed or infertile soils (Nongbet *et al*., 2022).

Seed priming with nanonutrient solutions enhances germination and early seedling vigor, establishing a foundation for higher yield (Yadav *et al*., 2023). Soil-applied slow-release nanoformulations provide steady nutrient supply across crop life cycle with fewer applications, reducing labor and costs (Rajput *et al*., 2023).

Integration with precision agriculture tools (remote sensing, soil sensors) facilitates tailored, site-specific nanoformulation application, optimizing nutrient use and yield responses (Mim *et al*., 2025).

Regional and Crop-Specific Responses: While the overall trend supports yield and quality improvements, response magnitude varies by crop species, soil type, and climatic conditions. Semi-arid and drought-prone zones typically show greater relative yield gains due to amelioration of moisture and nutrient stresses (Verma *et al*., 2024).

High-rainfall and irrigated environments benefit predominantly from reduced nutrient leaching and environmental losses through controlled-release nanofertilizers (Mejias *et al*., 2021). Cereals consistently show grain yield and quality boosts, while horticultural and tuber crops display pronounced improvements in sensory and nutritional qualities (Rajput *et al*., 2023).

Economic and Market Implications: Yield and quality improvements from nanofertilizers translate to higher farmer incomes due to better product quantity, reduced input costs due to higher nutrient-use efficiency, and better market prices from enhanced product quality (Rajput *et al*., 2023). Nanofertilizer-enabled biofortification aligns with global nutrition targets.

Nanofertilizers significantly improve crop yield and quality through efficient nutrient use, physiological optimizations, and stress mitigation. Their versatile delivery modes and compatibility with digital farming advance climate-resilient agricultural productivity. Tailored applications considering regional and crop-specific conditions will maximize benefits while supporting sustainable intensification.

Empirical Evidence of Enhanced Nutrient Use Efficiency

Several studies document NUE improvements and associated yield gains with nanofertilizer use:

- Wheat field trials report 20-55% increases in nitrogen use efficiency using nano-urea compared to conventional urea, yielding better biomass and grain production while using less nitrogen (Goyal *et al*., 2025; Mejias *et al*., 2021).
- Maize responded to nano-nitrogen and nano-zinc treatments with 20-30% increased nutrient uptake and aboveground biomass enhancement (Nongbet *et al*., 2022).
- Rice trials using nano-DAP combined with nano-iron increased phosphorus and iron uptake efficiency by 30-40%, significantly improving yields and grain nutrient content (Kale & Gawade, 2021).
- Potato tuber yield was maintained or improved with 25–50% reduced nitrogen and phosphorus nano-nutrient doses, illustrating resource savings and environmental benefits (Rajput *et al*., 2023).

3. Economic and Environmental Benefits

Improved NUE translates into reduced fertilizer input costs through decreased application frequency and rates, lowering production cost for farmers (Rajput *et al*., 2023). Additionally, precise nutrient targeting reduces environmental pollution from nutrient runoff, leaching, and greenhouse gas emissions (Mejias *et al*., 2021). These benefits collectively contribute to sustainable intensification and climate-smart agricultural practices (Yadav *et al*., 2023).

Integration with Precision Agriculture Technologies: Nanofertilizers complement precision agriculture by enabling site-specific nutrient management through sensor data and variable rate technologies (Mim *et al*., 2025). Real-time soil nutrient monitoring facilitates adaptive dosing of nanofertilizers ensuring nutrient supply matches spatial and temporal crop requirements (Goyal *et al*., 2025). This integration maximizes NUE gains and sustainable resource use.

Challenges and Future Perspectives:

Despite substantial benefits, challenges remain regarding nanofertilizer cost, production scalability, regulatory pathways, and long-term environmental safety (Ayenew, 2024). Future research aims to develop biodegradable nanomaterials, cost-effective nanoformulations, and robust safety evaluations to foster widespread adoption.

Nanofertilizers enhance nutrient use efficiency through controlled release, increased solubility, improved plant uptake, and synergistic root-microbial interactions. Empirical evidence supports their role in reducing fertilizer use while improving yields and environmental sustainability. Their integration with precision agriculture augurs well for future sustainable food production systems.

Yield Increase and Crop Quality Enhancement:
With the increasing global population and the intensifying impacts of climate change, boosting agricultural yield and improving crop quality have become essential goals to sustain food security and nutritional adequacy. Nanofertilizers, utilizing nanotechnology for precision nutrient delivery, have emerged as pivotal tools to achieve these aims by enhancing nutrient use efficiency and plant physiological functioning. Recent research across various crops and agroecologies demonstrates significant yield increases and quality improvements using nanofertilizers, positioning them as transformative inputs for sustainable agriculture (Goyal *et al*., 2025; Mejias *et al*., 2021).

Abiotic Stress Tolerance in Plants Enhanced by Nanofertilizers
Abiotic stresses—such as drought, salinity, temperature extremes, and heavy metal toxicity—pose substantial threats to global food security by adversely impacting plant growth and yield (Abdel-Aziz, 2023; Yang *et al*., 2025). The intensification and unpredictability of these stresses under climate change necessitate advanced approaches for augmenting crop resilience. Nanofertilizers, nanoscale nutrient formulations, have emerged as promising tools that enhance abiotic stress tolerance by improving nutrient delivery, regulating antioxidant defenses, and modulating stress-responsive physiological and molecular pathways (Goyal *et al*., 2025; Mim *et al*., 2025).

Underlying Physiological and Biochemical Processes:
Nanofertilizers modulate several key physiological and biochemical pathways:

- **Root Growth and Nutrient Uptake:** Enhanced root proliferation and hyphal development increase nutrient and water absorption surface area, aiding biomass accumulation and grain filling (Yadav *et al*., 2023).
- **Improved Photosynthesis:** Maintenance of chlorophyll content and photosynthetic enzyme activities ensures robust carbon assimilation, energy production, and biomass synthesis critical for yield (Mejias *et al*., 2021).
- **Antioxidant Defense:** Nano-enabled micronutrients enhance antioxidant enzyme function, protecting chloroplasts and cellular organelles from oxidative stress during critical development phases (Nongbet *et al*., 2022).
- **Hormonal Regulation:** Nanoparticle's influence phytohormones (auxins, cytokinins), affecting cell division, elongation, and reproductive organ development, ultimately enhancing yield components (Goyal *et al*., 2025).

Mechanisms Underpinning Stress Tolerance Enhancement: Nanoparticles improve plant abiotic stress tolerance primarily through:

1. **Activation of Antioxidant Défense Systems:** Abiotic stresses generate excess reactive oxygen species (ROS) leading to oxidative damage of proteins, lipids, and DNA. Nanofertilizers elevate activity of antioxidant enzymes including superoxide dismutase, catalase, and peroxidase, and increase levels of non-enzymatic antioxidants such as ascorbate and glutathione, mitigating ROS toxicity and preserving cellular integrity (Abdel-Aziz, 2023).
2. **Optimizing Nutrient Uptake and Homeostasis:** Nanofertilizers efficiently supply essential macro- and micronutrients (N, P, K, Zn, Fe, Mn), supporting metabolic functions impaired by abiotic stresses and enabling osmotic balance, enzymatic reactions, and photosynthesis under adverse conditions (Yang *et al*., 2025; Ahmad *et al*., 2025).

3. **Regulation of Stress-Responsive Genes and Phytohormones**: Nanoparticles influence gene expression involved in stress adaptation pathways and regulate hormone levels (abscisic acid, auxins, cytokinins), facilitating enhanced root growth, stomatal regulation, and metabolic adjustments (Selvakesavan *et al*., 2023; Páramo *et al*., 2023).
4. **Osmotic Adjustment and Membrane Protection:** Nanofertilizers promote accumulation of osmolytes (e.g., proline, soluble sugars) that preserve cell turgor and stabilize membranes, reducing electrolyte leakage and supporting cellular homeostasis during drought and salinity stress (Abdel-Aziz, 2023).
5. and protecting photosystems enable plants to sustain photosynthesis and energy production under stress, supported by improved nutrient status from nanofertilizers (Nongbet *et al*., 2022).

Applications and Effectiveness in Specific Stresses

Drought Stress: Si nanoparticles (SiNPs) significantly alleviate drought-induced water stress in crops like wheat and maize by improving relative water content, photosynthetic efficiency, and antioxidative capacity (Verma *et al*., 2024; Desoky *et al*., 2023). Nano-urea and micronutrient formulations enhance root hydraulic conductance and nutrient uptake, fostering drought resilience (Nongbet *et al*., 2022).

Salinity Stress: Salinity stress disrupts ionic balance and increases oxidative damage. Nano-zinc oxide and nanosilicon mitigate ionic toxicity by regulating Na^+/K^+ ratios and activating antioxidative mechanisms. Improvements in biomass, chlorophyll retention, and enzyme activities under saline conditions have been documented in rice and barley treated with these nanoforms (Kale & Gawade, 2021; Shelar *et al*., 2024).

Temperature Stress: Heat and cold stresses damage membranes and proteins. TiO_2 nanoparticles protect chloroplast membranes and increase antioxidant enzyme activities, reducing heat stress damage in tomatoes (El-Saadony *et al*., 2023). Nanosilicon aids cold tolerance by stabilizing membrane structures and osmolyte accumulation (Páramo *et al*., 2023).

Heavy Metal Toxicity: Nanofertilizers also alleviate heavy metal toxicity by chelating metals, reducing their uptake, and enhancing enzymatic detoxification. Studies show silica and metal oxide nanoparticles protect wheat seedlings exposed to copper and cadmium by elevating glutathione and antioxidative enzyme systems (Riaz *et al*., 2023; Shoukat *et al*., 2025).

Integration with Smart Precision Agriculture: Advances in nanosensor technologies enable real-time stress monitoring and tailor nanofertilizer application accordingly, optimizing plant response and resource use efficiency. This integration promises to refine stress mitigation strategies in variable field conditions.

While nanofertilizers bolster abiotic stress tolerance effectively, challenges include assessing long-term environmental impacts, cost-effective nanoparticle synthesis, and developing regulatory standards for safety (Ayenew, 2024). Further multi-disciplinary research is essential to realize their full potential sustainably.

Climate Change Mitigation and Adaptation:

Climate change poses unprecedented challenges to global agriculture through increased frequency of extreme weather, temperature fluctuations, altered rainfall patterns, and heightened pest pressures. Sustainable agricultural intensification to meet growing food demands necessitates technologies that enhance crop productivity while reducing greenhouse gas (GHG) emissions and improving system resilience (Goyal *et al*., 2025). Nanofertilizers, an emerging nanotechnology innovation in nutrient management, offer promising contributions to climate change mitigation and adaptation by improving nutrient use efficiency, reducing environmental losses, and bolstering plant stress tolerance (Yadav *et al*., 2023; Mejias *et al*., 2021).

Minimizing Greenhouse Gas Emissions: Agriculture contributes approximately 30% of total global GHG emissions, with nitrous oxide (N2O) from nitrogen fertilizer use as a major source (Zamora-Ledezma *et al*., 2025). Conventional fertilizers often exhibit low nitrogen use efficiency, leading to excess soil nitrogen susceptible to microbial transformations producing N_2O and ammonia volatilization.

Nanofertilizers mitigate GHG emissions through controlled-release formulations that synchronize nitrogen availability to crop uptake, dramatically reducing excess soil nitrogen pools fueling emissions (Mejias *et al*., 2021). Field studies demonstrate reductions of 20-40% in N_2O emissions using nano-urea relative to conventional urea across crops like wheat and maize (Nongbet *et al*., 2022). Improved synchrony diminishes nitrogen losses via leaching and denitrification pathways, contributing to climate change mitigation.

Also, certain nano-enabled micronutrients (e.g., nano-silicon) modulate soil microbial communities and redox conditions, further reducing methane emissions in flooded systems like rice paddies, reinforcing GHG mitigation (Singh *et al*., 2024).

Enhancing Resource Use Efficiency for Climate Adaptation

Nanofertilizers enhance crop resilience to climate-induced abiotic stresses by ensuring efficient nutrient delivery under variable moisture and temperature regimes. Their small particle sizes improve solubility and bioavailability even under constrained conditions, reducing nutrient deficiencies that limit stress tolerance (Nongbet *et al*., 2022).

Sustained nutrient supply fosters physiological processes such as osmotic adjustment, antioxidative enzyme activities, and photosynthetic efficiency critical for drought, salinity, and heat stress tolerance (Verma *et al*., 2024). Silicon and zinc oxide nanoparticles enhance antioxidant enzyme production, protecting cellular functions during oxidative stress episodes induced by climate extremes (Kale & Gawade, 2021).

Improved root development and microbial rhizosphere interactions stimulated by nanofertilizers also bolster water and nutrient uptake efficiency, enhancing survival and yield stability under climate variability (Mim *et al*., 2025).

Supporting Carbon Sequestration and Soil Health: Climate-smart fertilizer practices also target soil health preservation and carbon sequestration. Controlled nutrient release via nanofertilizers reduces over-fertilization that can accelerate soil organic matter mineralization and carbon loss (Ayenew, 2024). Enhanced nutrient availability without excessive inputs fosters greater biomass production and root exudate release, assets for soil organic carbon accrual.

Moreover, nanofertilizers promote soil microbial activities essential for organic matter turnover and nutrient cycling, underpinning soil carbon stabilization processes (Kalwani *et al*., 2022). These combined effects improve soil structure, moisture retention, and resilience to erosion, contributing to sustainable agroecosystem function amid climate pressures.

Integration with Digital and Precision Agriculture: Nanofertilizers are integral to emerging precision agriculture systems that optimize input use in space and time for climate resilience. Nanosensors provide real-time monitoring of soil nutrient status, moisture, and crop physiological indicators, enabling adaptive nanofertilizer application fine-tuned to dynamic field conditions.

Such integration markedly enhances nutrient use efficiency and mitigates off-target environmental impacts, key to sustainable intensification under climate uncertainty. Digital platforms enhance farmer decision-making facilitating effective nanofertilizer use even in smallholder and resource-poor contexts.

Challenges and Future Priorities

Despite proven potentials, challenges include ensuring long-term environmental safety of nanoparticles, cost-effective production at scale, regulatory oversight, and inclusive policies supporting adoption (Ayenew, 2024; Shoukat *et al*., 2024). Life cycle assessments quantifying net climate benefits of nanofertilizers under diverse cropping systems and geographies are critical.

Future research should focus on developing multifunctional nanofertilizers integrating nutrients with biostimulants and stress protectants, enhancing synergistic climate adaptation benefits (Mim *et al*., 2025). Public-private partnerships and capacity building programs will be essential to disseminate climate-smart nanofertilizer technologies globally.

Nanofertilizers contribute significantly to climate change mitigation by reducing nutrient-related greenhouse gas emissions and enabling precise input efficiency. Their role in enhancing plant resilience to climate-induced abiotic stresses supports adaptation efforts. Integration with precision agriculture and sustainable soil management positions nanofertilizers as vital components for resilient and low-carbon food production systems.

Future Directions

Nanofertilizers represent a transformative advancement in sustainable agriculture, offering prospects for enhanced nutrient use efficiency, yield improvement, and environmental conservation under climate uncertainty. Yet, to fully harness their potential, ongoing research, innovation, policy support, and field implementation strategies require comprehensive future directions focusing on technological, agronomic, environmental, and socio-economic dimensions (Goyal *et al*., 2025; Nongbet *et al*., 2022). This section elaborates key future avenues critical for advancing nanofertilizer benefits and integration into climate-resilient agricultural systems.

- **Advanced Nanomaterial Synthesis and Customization:** Future efforts must prioritize green, cost-effective, and scalable synthesis techniques producing biodegradable and environmentally benign nanomaterials customized to specific crop nutrient requirements and agroecological conditions (Mejias *et al*., 2021; Shoukat *et al*., 2024). Nanocarriers combining macro- and micronutrients with biostimulants or stress ameliorators will offer multifunctional solutions enhancing crop resilience and nutritional quality (Mim *et al*., 2025). Stimuli-responsive “smart” nanofertilizers that release nutrients triggered by specific soil or plant cues, such as pH, moisture, or root exudates, will enable unprecedented precision in nutrient management, reducing wastage (Yadav *et al*., 2023). Development of such advanced systems demand interdisciplinary research bridging nanotechnology, plant physiology, and soil science.

- **Integration with Precision and Digital Agriculture:** Nanofertilizers are poised for synergy with precision agriculture technologies like remote sensing, soil nutrient mapping, and AI-driven decision support systems (Mim *et al*., 2025). Real-time soil and crop nutrient status data will guide adaptive, site-specific nano-nutrient applications, optimizing input use and economic returns while mitigating environmental harms.
  Such integration requires development of nano sensors capable of detecting soil nutrient fluxes, crop stress markers, and environmental variables, enabling data-informed fertilizer management at a micro-scale. Investment in digital infrastructure and extension services will be critical to reach smallholder farmers and ensure adoption efficacy.
- **Expanding Crop and Agroecological Coverage:** While current research predominantly focuses on major cereals and commercial crops, future work must broaden to minor crops, horticulture, spices, and medicinal plants across diverse agroecological zones, including marginal and rainfed areas prone to climate stress. Tailored nano-nutrient formulations and crop-specific protocols will maximize applicability and impact on livelihoods.
  Field trials and long-term monitoring across heterogeneous soils and climate regimes will refine recommendations, promote region-specific adaptation, and build robust evidence for policymaking.
- **Environmental and Food Safety Evaluations:** Robust assessments of nanoparticle fate in soils, potential bioaccumulation, ecotoxicity, and food safety remain urgent priorities (Ayenew, 2024; Nongbet *et al*., 2022). Developing standards, regulatory frameworks, and safe-by-design principles will foster responsible innovation ensuring human and environmental health preservation.
  Research into green synthesis using natural polymers and biodegradable nanomaterials will mitigate potential ecological risks associated with nanoparticle persistence (Shoukat *et al*., 2024).
- **Socio-economic Research and Extension Models**
  Adoption studies analysing farmer perceptions, economic costs and benefits, and barriers across smallholder contexts are needed to design effective diffusion strategies (Rajput *et al*., 2023). Participatory extension models coupling demonstration trials, localized training, and digital advisory services will enhance acceptance and appropriate application.
  Policy incentives such as subsidies, certification for quality assurance, and inclusion in climate-smart agriculture programs will catalyse wider dissemination.
- **Multifunctionality and Integration with Biofertilizers:**
  Developing composite formulations integrating nanofertilizers with biofertilizers (beneficial microbes) and organic amendments offers potential for synergistic enhancement of soil health, nutrient cycling, and plant resilience (Nongbet *et al*., 2022). Exploring molecular interactions between nanomaterials and microbial consortia will guide tailored product design maximizing benefits. Integration supports circular bioeconomy principles and regenerative agriculture frameworks, enhancing sustainability and resilience.

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IMPACT OF PLASTIC POLLUTION ON MARINE LIFE

Nayomi Madhavaram[1*], Asritha Alli[2], Pebbeti Pooja[1] and Marikanti Karthik[3]

[1]PG Scholar, Department of Fisheries Resource Management
[2]PG Scholar, Department of Aquatic Environment Management
[3]PhD Scholar, Department of Aquaculture
*Corresponding Email: nayomimadhavaram24@gmail.com

Introduction

The marine and coastal environment is a zone of high productivity, containing vital subsystems like coral reefs and seagrass beds. A significant anthropogenic threat to these ecosystems worldwide is plastic pollution, which appears in multiple forms including litter, marine debris, plastic particle water pollution, and discarded fishing nets (Thushari & Senevirathna, 2020). The scale of this issue is immense, with global plastic production reaching approximately 280 million tons annually, used for a wide array of products from packaging to automobiles (as cited in Shaw & Sahni, 2014). This pollution consists of various polymers and additives, such as LDPE, HDPE, PET, and PVC, which contribute to the problem's complexity (Sigler, 2014). The consequences are severe, leading to the annual death of thousands of marine animals, including seabirds, sea turtles, and marine mammals, through ingestion or entanglement (Tekman *et al.,* 2022).

It is crucial to view plastic pollution as one of many interconnected stressors impacting biodiversity and ecosystems. The chemical pollution from plastics should be considered alongside other pressures like overharvesting, climate change, acidification, and habitat degradation (Tekman *et al.,* 2022). While the individual impact of a single stressor might seem small in isolation, the combined, additive, or synergistic effects of these multiple stressors can push species and ecosystems past critical thresholds, contributing to a potential mass extinction event (Tekman *et al.,* 2022). Since plastic pollution is accumulating globally in remote oceans, coastlines, and even deep-sea sediments, and is considered a planetary boundary threat, action is necessary even without absolute scientific certainty of every harm (Tekman *et al.,* 2022).

Impacts on Seabirds

Seabirds, a diverse group including albatrosses, gulls, and penguins, face numerous threats. Global assessments indicate that the primary dangers to seabirds are bycatch, climate change, and invasive species, with plastic pollution currently linked to population declines in only a few species, such as the flesh-footed shearwater (Tekman *et al.,* 2022). However, plastic ingestion is predicted to affect nearly all seabird species within decades. Research on the Laysan albatross provides a stark example; studies dating back to the 1960s show a high prevalence of plastic in their digestive systems, with parents inadvertently feeding plastic to their chicks (Tekman *et al.,* 2022). While plastic is rarely the direct cause of death, chicks with more plastic have lower body weight, which indirectly increases mortality risk, and ingested microplastics can introduce hazardous chemicals into their bodies (Tekman *et al.,* 2022).

Impacts on Sea Turtles

All seven species of sea turtles are endangered, facing threats from overharvesting, bycatch, habitat alteration, and pollution. Plastic pollution poses a significant danger through both ingestion and entanglement, which can lead to severe injuries like limb amputations and death

(Tekman *et al.,* 2022). The critically endangered hawksbill sea turtle, for instance, has shown evidence of plastic ingestion and entanglement since the 1970s in various locations around the world, from Costa Rica to Australia (Tekman *et al.,* 2022). A major challenge in studying the impact on such rare species is the small sample sizes available, making it difficult to estimate the overall effect of plastic pollution accurately (Tekman *et al.,* 2022).

Impacts on Marine Mammals

Pollution, including plastic debris, is a major threat to marine mammals, affecting 99 out of 123 species. A dramatic illustration of this is the necropsy of 30 sperm whales stranded in the North Sea in 2016, which revealed that 22 had plastic debris in their stomachs, including items like nets, bags, and car parts (Tekman *et al.,* 2022). Similar cases of ingestion and entanglement have been reported globally for sperm whales and other cetaceans. Broader studies, such as one conducted over 16 years in the Canary Islands, found that deep-diving species are at a higher risk of ingesting plastic, with items like bags and caps being most common (Tekman *et al.,* 2022).

Impacts on Sharks and Rays

While the primary threat to sharks and rays is overfishing, which has caused a 71% population decline since 1970, plastic pollution also has an impact (Tekman *et al.,* 2022). Entanglement, primarily in lost fishing gear, has been documented for at least 34 species of sharks and rays. For example, plastic rings can become wrapped around a shark's gills, causing severe abrasions and potentially hampering feeding and breathing as the animal grows (Tekman *et al.,* 2022). The endangered whale shark, as a filter feeder, is particularly vulnerable to microplastics; studies suggest they may ingest thousands of particles per day, and harmful plastic additives have been found in their tissues (Tekman *et al.,* 2022). Entanglement and ingestion of larger plastic items have also been recorded, sometimes leading to fatal injuries.

Impacts on Coral Reefs

Coral reefs, often called the "rainforests of the sea" due to their immense biodiversity, are severely threatened by microplastics. Corals can ingest microplastics directly or consume polluted zooplankton, which can disrupt their physiological functions and symbiotic relationships with algae (Tekman *et al.,* 2022). Experiments show that microplastics can suppress photosynthesis in symbiotic algae, leading to coral bleaching and tissue necrosis. Furthermore, microplastics often adhere to the exterior of corals, imposing additional energetic costs for cleaning and potentially reducing their energy reserves for survival and reproduction (Tekman *et al.,* 2022).

Impacts on Seagrasses and Mangroves

Seagrass meadows and mangrove forests are critical coastal ecosystems facing multiple stressors, including plastic pollution. Seagrass meadows can trap microplastics, becoming a sink for this pollution. The microplastics are then ingested by invertebrates living in the meadows, introducing plastic into the marine food web (Tekman *et al.,* 2022). Similarly, mangrove forests, which provide vital services like coastal protection and carbon sequestration, are threatened by habitat loss and fragmentation. While plastic pollution adds to these pressures, the most significant threats to mangroves remain deforestation and sea-level rise (Tekman *et al.,* 2022). Conservation of both seagrass and mangrove ecosystems requires widespread changes in human activities and dedicated protection measures.

Conclusion

Plastic pollution has emerged as a pervasive and intensifying anthropogenic stressor within marine and coastal ecosystems, distinguished by its vast spatial extent and chemical heterogeneity. It must be understood not as an isolated environmental issue, but as one component of a broader suite of interrelated pressures including climate change, overexploitation of resources, and habitat degradation that collectively exert cumulative and potentially synergistic effects on biodiversity. These converging stressors threaten to push vulnerable species and ecosystems beyond ecological thresholds, thereby reinforcing the classification of plastic pollution as a planetary boundary concern that demands precautionary and proactive intervention, even in the face of residual scientific uncertainty.

The ecological consequences of plastic pollution are both severe and taxonomically widespread. Seabirds, exemplified by the Laysan albatross, exhibit high rates of plastic ingestion, resulting in sublethal effects such as reduced chick body mass and the bioaccumulation of toxic compounds, with projections indicating near-universal exposure across avian taxa. Sea turtles, many of which are endangered, face acute risks from entanglement and ingestion, although population-level assessments remain constrained by limited empirical data. Marine mammals, particularly deep-diving cetaceans like sperm whales, demonstrate significant vulnerability, as evidenced by necropsy data revealing substantial ingestion of plastic debris. Elasmobranchs, while primarily threatened by overfishing, also suffer from entanglement in derelict fishing gear and, in the case of filter-feeding species such as whale sharks, ingestion of microplastics and associated chemical additives.

Critical marine habitats are similarly affected. Coral reefs experience physiological stress, bleaching, and tissue necrosis due to microplastic adhesion and ingestion, while seagrass meadows function as sinks for microplastics, facilitating their incorporation into marine food webs. Although mangrove ecosystems are more immediately imperiled by deforestation and sea-level rise, plastic pollution compounds the cumulative burden on these essential coastal buffers. Collectively, these findings underscore the role of plastic pollution as a significant driver of injury, physiological impairment, and elevated mortality across marine biota.

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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