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KALIA: A BOLD STEP TOWARD FARMER WELFARE AND INCLUSIVE GROWTH IN ODISHA

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In the initial post-independence years, Indian agriculture was plagued by low productivity, excessive reliance on monsoons, inadequate infrastructure, and frequent food shortages. The Green Revolution initiated in the mid-20th century revolutionized with high-yielding variety (HYV) seeds, the more extensive use of fertilizers and pesticides, and efficient irrigation systems, and facilitated India's shift from food shortage to self-sufficiency. However, despite these advancements, many structural challenges, particularly farmer distress and income insecurity, still persist in the sector.

Recent farmer agitations have brought the focus on these problems, and it is high time more specific and inclusive solutions are adopted. Direct Income Support (DIS) is one such strategy, a policy change from blanket subsidies to direct financial aid. Both the state and central governments in the past few years have launched DIS programmes such as Telangana's Rythu Bandhu, Odisha's KALIA, and the Centre's PM-KISAN, aiming to reach farmers more effectively. Odisha's Krushak Assistance for Livelihood and Income Augmentation (KALIA) scheme has been a path-breaking model among them.

The Genesis and Vision of KALIA

The KALIA scheme, a flagship initiative of the Government of Odisha was launched in 2018. It aimed at transforming the rural economy through direct support to all categories of farmers, viz., sharecroppers, marginal landowners, and landless farming households.

In contrast to other schemes that are confined to landowners, KALIA adopts a more inclusive approach to cover the most vulnerable stakeholders in the agricultural value chain. KALIA is a more inclusive approach which cover the most vulnerable stakeholders in the agricultural value chain, unlike other programs limited to landowners only.

In its first phase alone, KALIA disbursed ₹2,500 crore to over 51 lakh farmers within four months demonstrating both administrative efficiency and political will.

Key Objectives of the Scheme

- To provide financial assistance to farmers and agricultural labourers for cultivation and livelihood activities.
- To reduce the burden of debt and dependency on informal credit.
- To promote sustainable agriculture and support income diversification.
- To improve financial inclusion and reduce poverty among rural households.
- To enhance the overall socio-economic well-being of farming communities, especially women, SC/ST, and other vulnerable groups.

Components of the KALIA Scheme

Component	Description
Cultivation Support	₹10,000 per annum (₹5,000 per season) for small and marginal farmers to purchase inputs like seeds and fertilizers.
Livelihood Support	One-time financial assistance of ₹12,500 to landless agricultural households for allied activities such as goat rearing, fisheries, mushroom cultivation, etc.
Vulnerable Household Assistance	₹10,000 per vulnerable household (including elderly, disabled, and widows) unable to cultivate land or undertake livelihood activities.
Life Insurance	₹2 lakh insurance cover with a nominal premium of ₹330 per annum, of which ₹165 is paid by the government.
Interest-Free Crop Loans	Up to ₹50,000 crop loans at 0% interest for farmers, including sharecroppers and oral lessees.

Source: Department of Agriculture & Farmers' Empowerment, Government of Odisha, 2024
(*However, KALIA scheme was renamed as CM-KISAN by the government of Odisha in the year 2024. With the renaming of the KALIA scheme, the financial assistance component of the scheme changed. The financial assistance has been reduced from ₹10,000 per annum to ₹4,000 per annum).

Distinctive Features of the KALIA Scheme

- **Data-Driven Targeting:** This program uses over 20 citizen and service databases such as the Socio-Economic Caste Census (SECC) and National Food Security Act (NFSA) records to select beneficiaries for the scheme to maintain high degree of accuracy.
- **Digital Governance and Privacy**: All data collection is done by taking the consent of the concerned beneficiary. The data is safely stored and disclosed only to permitted officials under a privacy-by-design framework.
- **Technology-Enabled Delivery:** KALIA is constructed on an open digital ecosystem that includes banking, welfare and agriculture related services integrated in the digital ecosystem. It has facilitated a consolidated farmer database for targeted outreach.
- **Grievance Redressal Mechanism:** An innovative online and offline grievance mechanism, with access via Common Service Centres (CSCs), has redressed close to 10 lakh grievances—exhibiting transparency and accountability.

Advantages of the KALIA Scheme

1) **Holistic and Inclusive Support :** KALIA goes beyond conventional subsidy models by extending the support to landless labourers, sharecroppers, and other excluded groups, offering them cultivation support, livelihood assistance, and social security.
2) **Boost to Agricultural Productivity :** Under the scheme, funds are released timely before every cropping season which allows farmers to purchase quality seeds and fertilizers which in turn lead to improvement in crop output and farm returns in both Kharif and Rabi seasons.
3) **Promotion of Diversified Livelihoods :** Activities such as goatery, mushroom cultivation, and beekeeping are promoted through the scheme thus facilitating rural entrepreneurship and also diversification from a single income-generating source.
4) **Financial Inclusion and Less Indebtedness :** By providing direct cash transfers, interest-free credit, and insurance cover, KALIA minimizes the necessity for farmers to approach informal money lenders.

5) **Social Empowerment and Equity :** The scheme benefits families which are women-led and vulnerable groups, thereby promoting and contributing to gender equity, rural stability, and less migration.

Challenges and Limitations

1) **Large Fiscal Burden :** The extensive financial expenditure needs sustained funding, which could strain the fiscal resources of the state and push away other development priorities.
2) **Inefficiency in Targeting :** Errors in exclusion and inclusion errors have been witnessed, where some actual beneficiaries have been excluded and ineligible persons have been included.
3) **Lack of Exit Strategy :** Since there is no provision for complementary investment in irrigation, marketing infrastructure, and extension services, the scheme could lead to dependency on government rather than long-term empowerment.
4) **Leakage and Administrative Risks :** Although the online platform reduces corruption, localized errors and tampering could remain, which might erode trust.
5) **Limited Structural Reform :** The program addresses income support but does not directly address concerns such as land fragmentation, irrigation bottlenecks, or poor market access, which need fundamental policy changes.

KALIA vs. Other Income Support Schemes: A Comparative Perspective

To better understand the uniqueness of the KALIA scheme, it is helpful to compare it with other prominent income support initiatives, particularly the central government's PM-KISAN and Telangana's Rythu Bandhu.

Feature	KALIA (Odisha)	PM-KISAN (Central)	Rythu Bandhu (Telangana)
Launch Year	2018	2019	2018
Eligibility	Small, marginal, landless farmers, sharecroppers, vulnerable groups	All landholding farmer families (up to 2 ha initially; now all)	All land-owning farmers
Type of Support	Income support for cultivation, livelihood, insurance, loans	Income support only	Income support only
Amount	₹10,000 per year (cultivation) + livelihood + insurance + interest-free loans	₹6,000 per year (in 3 instalments)	₹10,000 per year (₹5,000 per season)
Inclusion of Landless	✓	–	–
Livelihood Diversification Support	✓ (e.g., goat rearing, fisheries)	–	–
Insurance and Credit Linkages	✓	–	–
Use of Technology for Targeting	✓ Advanced (20+ databases, digital grievance redressal)	Moderate (mostly Aadhaar-based DBT)	Moderate

Source: Comptroller and Auditor General of India, 2024; Department of Agriculture & Farmers Welfare, Government of India, 2020

Key Takeaways from the Comparison

- **Inclusiveness:** KALIA is the most inclusive scheme among the three discussed here. KALIA covers landless households, sharecroppers, and vulnerable farmers, which are often excluded from other schemes.
- **Comprehensiveness:** KALIA combines income support measures with livelihood promotion, insurance, and credit, making it a multi-dimensional rural welfare package which are lacking in PM-KISAN and Rythu Bandhu,
- **Technology Use:** KALIA leverages advanced data integration and grievance redressal mechanisms, making it more transparent and accountable.

This comparison reveals that although PM-KISAN and Rythu Bandhu offer wider or easier coverage, KALIA stands out in terms of depth, precision in targeting, and social inclusiveness.

Conclusion

The KALIA scheme is a progressive policy towards farmers' well-being and socio-economic upliftment. It combines inclusiveness, financial empowerment, and digital governance. It is not only a financial support mechanism but also a rural transformation platform. In order to remain successful in the long run, it must link up with larger rural development schemes, including infrastructure building, establishing market connections, and fostering climate-resilient agriculture. Since other states and the government at the center look for replicable models in farmer welfare, KALIA provides valuable lessons on inclusive design, technology adoption, and accountable governance.

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REAPING BENEFITS OF BIOTECHNOLOGY IN INDIAN AGRICULTURE

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India's economy relies heavily on agriculture, which provides a livelihood for a large part of its population. Following independence, the sector underwent a significant transformation, shifting away from traditional subsistence farming toward a more industrialized approach. A key event was the Green Revolution of the 1960s, which introduced new technologies, including high-yielding crop varieties, chemical fertilizers, and improved irrigation methods. Today, the Indian agriculture sector faces challenges like fragmented landholdings, limited water availability, a shortage of fertilizer and soil degradation. Climate change is making things worse, causing unpredictable weather, droughts, and floods that put crop yields at risk. Further, agricultural production approached a bottleneck due to limited arable land, extreme weather, and the yield plateau of conventional breeding methods. Modern biotechnology tools with improved specificity and efficiency could eventually become the main driver of agricultural improvement, overcoming the limitations of conventional practices in improving crops. Biotechnology is a field that utilizes living organisms or their components to develop new products and technologies. It uses a range of techniques that can modify and improve biological systems for a specific purpose. Through techniques like molecular marker, genome sequencing, omics, genetic engineering and tissue culture, scientists can create crops that are more resilient to modern issues such as water scarcity, climate change, disease and pests. Biotechnology significantly benefits Indian agriculture by increasing crop yields along with enhancing nutritional content in crops, and improving resistance to pests and diseases that reduces pesticide use and environmental damage. Biotechnology also creates climate-resilient crops tolerant to drought and salinity, supports sustainable farming practices, and offers economic advantages for farmers by improving productivity and reducing losses.

1. Molecular Marker Technique

A molecular marker is a specific fragment of DNA that is associated with a certain gene or trait. Because the marker and the desired gene are located close together on the same chromosome, they are almost always inherited as a pair.

Table 1: Major Biotechnology applications in the agriculture sector

Sr. No.	Biotechnology technique	Application	Success story
1.	Molecular Markers	Marker-assisted selection, identification of complex traits	**Rice:** Improved Pusa Basmati 1 and Improved Samba Mahsuri, Improved Lalat, Improved Tapaswini, DRR Dhan 59, Swarna Sub 1 **Wheat:** PBW 761 (Unnat PBW 550), PBW 752 **Maize:** Vivek QPM9, Pusa HM4 Improved, Pusa HQPM-5 Improved **Pearl Millet:** HHB 67 Improved, HHB 67 Improved 2 **Chickpea:** Super Annigeri-1, Pusa Chickpea 20211

Sr. No.	Biotechnology technique	Application	Success story
			Soybean: NRC 127, NRC 132 **Groundnut:**Girnar 4, Girnar 5
2.	Transgenic technology	Developing a novel crop/plant with a transgene	***Bt* Crops:** *Bt* Cotton, *Bt* Corn **Herbicide-Tolerant Crops:** Roundup Ready Soybeans **Golden Rice:** beta-carotene rich **Virus-Resistant:** Papaya
3.	Omics technology	Genomics, transcriptomics, proteomics, metaboliomics, etc.	Identified key genes and quantitative trait loci (QTLs) associated with desired traits Genomic-based selection strategies (GBS)
4.	Genome editing	Precise modification of the individual	**Rice**: DRR Dhan 100 (Kamala), Pusa DST Rice 1

Molecular markers have been a game-changer for crop breeding in India, particularly in developing varieties that can offer resistance/tolerance against various biotic and abiotic stresses. Indian scientists from various institutions explored molecular marker-assisted selection (MAS) to select a crop with desirable traits. This allows them to quickly find and combine multiple genes for disease resistance, such as the *Xa13* and *Xa21* genes, into popular rice types like Pusa Basmati 1 and Samba Mahsuri. Because MAS and/or marker technology much faster and more precise than traditional breeding, India has been able to release several new, high-yield varieties of rice. This has helped improve food security and reduced the need for farmers to use chemical pesticides.

2. Transgenic technology

Transgenic technology in plants involves the introduction of a foreign gene called a transgene into a plant's genome to give it a new, desirable trait that it doesn't naturally possess. This process, also known as genetic engineering or genetic modification, creates a transgenic plant or Genetically Modified Organism (GMO). This technique is of great importance in agriculture because it allows scientists to introduce specific, desirable traits into crops that cannot be achieved through traditional breeding methods. This technology addresses key challenges in modern farming, such as pest management, nutritional deficiencies, and environmental stress ultimately contributing to increased productivity and food security. Major achievement of this technique is Bt cotton that has had a profound and complex impact on Indian agriculture since its introduction in 2002. As a genetically modified (GM) crop, it has been a major force in transforming India from a net importer of cotton to one of the world's leading producers and exporters. Biotechnology also helps to improve the nutritional quality of our food. Through a process called biofortification, One well-known example Vitamin A-enriched "Golden Rice" and nutrient-rich millets, are being developed to address hidden hunger and malnutrition in India. Another major advantage of GM technology one can create drought-tolerant, salinity-tolerant, and heat-resistant crop varieties, crucial for farmers in areas facing water scarcity and unpredictable weather patterns due to climate change. Thus, by reducing the need for chemical fertilizers and pesticides, biotechnology contributes to a healthier ecosystem, prevents groundwater contamination, and supports sustainable farming.

3. Omics technology

Omics technology is a field of biology that focuses on the large-scale analysis of biological molecules to gain a comprehensive understanding of an organism. The name comes from the suffix "-omics," which refers to the study of a complete set of something. Instead of studying a single gene or protein, omics technologies study entire sets of genes, proteins, or other molecules to see how they interact and influence an organism's function. Several branches of omics technology have emerged, each focusing on a different level of biological information. The most common ones include:

A. **Genomics:** It is concerned to study of an organism's entire set of genes, called the **genome**. Here, scientist use DNA sequencing to identify all genes and understand their structure, function, and interactions.
B. **Transcriptomics:** It is concerned to studies the **transcriptome**, which is the complete set of RNA molecules transcribed from the DNA at a given time. It shows which genes are actively being expressed and at what level.
C. **Proteomics:** It is concerned with large-scale study of the **proteome**, the entire set of proteins produced by an organism. Proteins carries out most biological functions.
D. **Metabolomics:** It is concerned on **metabolome**, that id consists of all the small-molecule metabolites (e.g., sugars, amino acids, fatty acids) present in a cell or organism.

4. Genome editing

Genome editing, or gene editing, is a group of technologies that allow scientists to make precise changes to an organism's DNA. This includes adding, removing, or altering genetic material at specific locations in the genome. The most famous and widely used of these technologies is CRISPR-Cas9, which is a powerful, efficient, and relatively simple tool. Genome editing technology has emerged as a revolutionary tool in agriculture, providing a high level of precision and speed that was previously impossible. Unlike older genetic modification techniques that often involve inserting foreign genes, genome editing allows for targeted changes to a plant's existing DNA, making the process faster and often leading to crops that are not subject to the same strict regulations.Indian scientists, particularly from the Indian Council of Agricultural Research (ICAR), have developed two landmark genome-edited rice varieties.

In conclusion, while the Green Revolution was a pivotal moment that successfully addressed India's immediate food security concerns, it also laid the groundwork for complex and interconnected modern challenges. The reliance on intensive farming practices has led to environmental degradation, while climate change poses an existential threat to crop predictability and yield. However, the emerging field of biotechnology presents a powerful and timely solution. By leveraging advanced techniques such as molecular markers, genetic engineering and genome editing, India's agricultural sector can develop crops that are not only high-yielding with high nutritional value but also inherently more resilient to pests, diseases, and environmental stresses like drought and salinity, promoting sustainable practices. Therefore, the future of sustainable and productive Indian agriculture may hinge on its successful and widespread integration of biotechnology, ensuring that the sector continues to support the nation's population for generations to come.

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AGRICULTURE IN THE AGE OF CLIMATE UNCERTAINTY: IMPACTS, RISKS AND FUTURE PERSPECTIVES

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Abstract

Agriculture is both a victim and a contributor to climate change. Uncertainties in climate- including variability in seasonal precipitation, frequency and intensity of extremes (droughts, floods, heatwaves), and shifting pest and disease regimes - create significant risks for crop yields, livestock productivity, and food systems. At the same time, agricultural activities contribute roughly a quarter of anthropogenic greenhouse gas emissions globally (including CO_2, CH_4 and N_2O), creating an urgent need for mitigation alongside adaptation. Rising temperatures, erratic rainfall, and extreme events amplify risks for smallholders and global supply chains alike. These challenges demand integrated approaches combining climate-resilient crops, sustainable resource management, and advanced technologies such as remote sensing, digital tools, and AI-driven climate services. Building adaptive capacity through policy support, innovative practices, and farmer-cantered knowledge systems is crucial for ensuring long-term resilience. Future perspectives highlight the need for cross-sectoral strategies, inclusive governance, and investment in climate-smart solutions to safeguard food systems against growing uncertainties. This paper aims at highlighting the impacts, risks, and strategic responses related to climate uncertainty.

Introduction

Agriculture is the backbone of food security, providing livelihoods to over 2.5 billion people and feeding a global population that is projected to reach 9.7 billion by 2050 (FAO, 2022). However, the sector is increasingly threatened by climate uncertainty, marked by erratic rainfall, rising temperatures, extreme weather events, and shifting pest and disease pressures. These risks undermine productivity, food availability, and farmer livelihoods, while intensifying market volatility and resource stress. Ensuring food security in this context demands strategies that strengthen resilience and reduce emissions. Key responses include the adoption of climate-smart practices, drought- and heat-tolerant crop varieties, improved water and soil management, and ecosystem-based approaches. At broader scales, risk insurance, adaptive governance, and integrated policies are critical to manage shocks and safeguard vulnerable communities. By advancing mitigation–adaptation synergies and fostering inclusive, evidence-based interventions, agriculture can remain viable and food systems more secure in an uncertain climate future. In this context, exploring the impacts, risks, and future perspectives of agriculture in the age of climate uncertainty becomes critical. Understanding these dimensions enables stakeholders to identify adaptation pathways, adopt innovative technologies, strengthen institutional mechanisms, and build climate-resilient food systems. This paper highlights the major vulnerabilities of agriculture to climate uncertainty, analyses associated risks, and outlines strategies and future directions to ensure sustainable agricultural development in an increasingly unpredictable climate.

Defining Climate Uncertainties

Climate uncertainties refer to unpredictable fluctuations and extremes in weather and climate parameters, including Temperature anomalies (heatwaves, cold spells, shifting growing seasons), rainfall variability (delayed monsoons, prolonged dry spells, erratic distribution), extreme weather events (cyclones, floods, droughts, hailstorms) and biological uncertainties (pests, vector-borne diseases, invasive species influenced by climate change). Agriculture is highly climate-sensitive. Crop growth, livestock performance, soil fertility, and water availability are all influenced by weather conditions. Unlike other economic sectors, agriculture operates largely in open systems directly exposed to climatic risks.

Climate Uncertainties and Agricultural Systems

1. Temperature Rise and Heat Stress:

Global average surface temperature has already increased by more than 1.1°C compared to pre-industrial levels (IPCC, 2023), and further increases are inevitable. Even minor deviations in temperature can have outsized impacts on agriculture.

1.1. Crop Yields: Climate change reduces Indian crop yields by decreasing rainfall, causing heat stress, and increasing extreme weather events like droughts and floods, which damage crops and disrupt food security. Key staple crops such as wheat, rice, and maize are particularly vulnerable, facing projected significant yield reductions in the coming decades due to higher temperatures and changes in precipitation. Increased CO_2 levels also diminish crop nutrition, lowering protein, iron, and zinc content. High temperatures shorten the growing season by accelerating crop maturity, reducing time for photosynthesis and grain filling. For instance, a 1°C increase in temperature during the growing season can reduce wheat yields by 6-10% in South Asia.

1.2. Pollination Failure: Climate change leads to crop pollination failure through disruptions in flowering, increased heat stress causing premature flower drop, altered rainfall patterns, and reduced pollinator populations and efficiency. Higher temperatures and prolonged dry spells reduce nectar production, directly impacting pollinator health and numbers, while unpredictable, unseasonal rains can damage crops or hinder seed development. These factors threaten India's major crops like wheat, rice, and pulses, jeopardizing national food security and farmer livelihoods. Heat waves during the flowering stage can lead to pollen sterility in crops such as rice, maize and pulses, significantly reducing productivity.

1.3. Livestock Stress: Cattle, poultry, and small ruminants are highly sensitive to heat. Rising temperatures reduce feed intake, fertility, and milk yield, while also increasing mortality in serve cases.

2. Rainfall Variability

Rainfall is the most critical factor impacting agricultural productivity, particularly in regions dominated by rainfed farming. Climate uncertainties disrupt both the timing and quantity of precipitation.

2.1. Erratic Monsoons: Climate change is making Indian monsoons erratic by increasing the frequency and intensity of heavy rainfall, leading to both floods and droughts, and altering their timing. This is due to a warmer atmosphere and changing ocean temperatures, resulting in shorter, more intense downpours and longer dry spells, which devastates agriculture, water security, and the broader economy. In India, delayed monsoons affect the sowing of rice and pulses, while early withdrawal reduces soil moisture needed for post-monsoon crops.

2.2. Droughts and Dry Spells**:** Climate change is increasing the frequency and severity of droughts and dry spells in India by creating compound warm-dry spells where extreme heat and low rainfall occur together, leading to intensified drying of soils and increased atmospheric water demand. While overall rainfall might be decreasing in some regions, such as Kerala and the Northeast, other areas like North Karnataka and Maharashtra are experiencing more intense downpours followed by extended dry gaps, a "flood-to-drought whiplash" effect that exacerbates drought conditions and reduces crop yields. These events are leading to reduced agricultural productivity and increased vulnerability across various regions, particularly in central India. Prolonged periods without rainfall, damage germination, reduce soil moisture, and increase irrigation demand. India's Bundelkhand region is particularly vulnerable.

2.3. Excess Rainfall and Flooding**:** Climate change is increasing excess rainfall and intensifying flooding in India by altering monsoon patterns and leading to shorter, more intense bursts of rainfall. This combination of heavy downpours after long dry spells can overwhelm drainage systems, causing severe urban and widespread riverine floods, threatening lives, property, and agriculture. A projected rise in global temperatures could make extremely wet monsoons, previously rare, a frequent occurrence in India, intensifying the severity of these floods. Sudden heavy downpours waterlogged fields, destroy crops, and erode topsoil. Floods also lead to loss of stored grains and infrastructure damage.

3. Extreme Weather Events

The frequency and intensity of extreme weather events have increased in recent decades and the trend as projected below is to continue.

3.1. Cyclones and Hurricanes**:** The research confirms that climate change is leading to increasingly intense, longer-lasting, and more frequent cyclones in the North Indian Ocean region, particularly in the Arabian Sea, due to rising sea surface temperatures and warmer, more humid air. This intensified cyclonic activity poses significant risks to India's coastal regions, impacting infrastructure, livelihoods, and overall vulnerability to extreme weather events. Coastal agricultural zones suffer from storm surges, saline water intrusion, and crop destruction.

3.2. Hailstorms**:** Climate change is increasing the frequency, intensity, and duration of severe tropical cyclones in the North Indian Ocean region, particularly the Arabian Sea, due to rising sea surface temperatures and other atmospheric changes. While the total annual frequency of cyclones may have decreased, the number of very severe storms and their intensity has risen, leading to significant socio-economic impacts and increased vulnerability for India's coastal regions. Unseasonal hail causes widespread crop damage, particularly fruits and vegetables.

3.3. Droughts**:** Climate change is increasing the frequency, intensity, and duration of droughts in India, particularly by increasing evapotranspiration and altering monsoon patterns. Rising temperatures are exacerbating the problem, leading to significant impacts on agriculture, water security, and economic stability, with projections for further escalation of drought severity across the nation.

4. Pests and Diseases:

Climate uncertainties also create favorable conditions for pests and diseases, destabilizing production systems as mentioned below:

- Warmer temperatures allow pests like the fall armyworm to spread into previously unsuitable regions.
- Humid conditions promote fungal diseases such as wheat rust and rice blast.
- Vector-borne diseases (e.g., bluetongue, Rift Valley fever) are becoming more prevalent as climate conditions favour vector survival.

5. Combined and Cascading Effects

The most serious risks often arise from cascading interactions: a drought followed by locust outbreaks, or flooding followed by waterborne livestock diseases. These compound events intensify agricultural losses and make recovery difficult for smallholder farmers.

6. Soil and Water Resource Degradation

- ***Soil Erosion and Degradation***: Intense rainfall and flooding events lead to accelerated soil erosion, stripping away fertile topsoil that is essential for plant growth.
- ***Water Erosion*****:** Heavy downpours, increasingly common under climate change, wash away soil nutrients and reduce organic matter content. For example, the Indo-Gangetic plains of India lose an estimated 16 tons of soil per hectare annually due to water erosion**.**
- ***Wind Erosion*****:** Prolonged droughts and dry spells expose soils to wind erosion, a growing concern in semi-arid regions of Africa and western India.
- ***Declining Fertility:*** Climate change significantly reduces soil fertility in India through increased soil erosion from intense rainfall, loss of soil organic carbon from rising temperatures, and disrupted nutrient cycles, all of which degrade the soil structure and its capacity to hold water and nutrients, ultimately decreasing crop yields. Extreme weather events, altered rainfall patterns, and prolonged dry spells exacerbate these effects, contributing to a broader soil health crisis and threatening the nation's food security. Soil nutrient imbalances, including nitrogen loss through volatilization under high temperatures, reduce crop yields.

7. Desertification and Land Degradation

Climate uncertainties exacerbate desertification in already fragile ecosystems with the following impacts.

- ***Expansion of Arid Zones***: Climate change is expanding arid zones in India, though recent studies also show localized greening due to increased rainfall and human activity, particularly in the Thar Desert. While global trends show increased aridity, India is experiencing complex shifts, including a westward expansion of the monsoon bringing more rainfall to arid regions. However, increased drought frequency and severity, intensified by both natural and human factors, pose significant risks of desertification and land degradation, particularly in western, central, and southern India. Rising temperatures and lower rainfall lead to desert encroachment, particularly in parts of Rajasthan in India.

- ***Loss of Arable Land:*** Land degradation in India results in the loss of fertile soils due to factors like deforestation, overgrazing, poor irrigation practices, mining, urbanization, and industrial activities. These human-induced activities, exacerbated by natural factors like drought and soil erosion, lead to a decline in the physical, chemical, and biological properties of the soil, reducing its fertility and productivity. India experiences approximately 21 tonnes of soil loss per hectare per year, with some highly vulnerable areas like the Brahmaputra Valley facing much higher rates. This significant loss amounts to an estimated 5.3 billion tonnes of soil annually due to factors such as deforestation, intensive farming practices, and natural causes like heavy rainfall. Globally, 24 billion tons of fertile soil are lost annually (UNCCD, 2022), reducing the availability of land for cultivation.

- ***Vegetation Loss:*** Climate change is contributing to vegetation loss in India through increasing temperatures, erratic rainfall, and droughts, which stress plants, increase pest and disease outbreaks, and decrease soil moisture, ultimately reducing the health and biomass of forests and farmland. Studies show significant forest and agroforestry tree losses, with rainfall and temperature shifts acting as major drivers of degradation, particularly impacting the Northeast and areas like the Ziro Valley and Loktak Lake. Droughts diminish natural vegetation cover, which in turn accelerates erosion and land degradation.

8. Water Scarcity and Groundwater Depletion:

In India, climate change exacerbates water scarcity and groundwater depletion by causing more extreme rainfall patterns, prolonged droughts, and increased temperatures, forcing farmers to over-extract groundwater for agriculture. This creates significant economic and social hardship, especially for rural communities, by reducing crop yields and incomes. Key regions like the Northwest and parts of the South and West are particularly vulnerable. Addressing these challenges requires improved water resource management, sustainable irrigation, and policy reforms to promote groundwater conservation and build climate resilience.

- ***Rainfall Variability:*** Climate change is increasing rainfall variability in India by shifting patterns, with more frequent dry spells and more intense wet spells, leading to more heavy rainfall days and greater extremes in both wet and dry conditions. While some regions see a significant increase in southwest monsoon rainfall, others, particularly in the Indo-Gangetic Plains and parts of the Himalayas, are experiencing significant decreases. This creates a "drier-wetter" pattern, with wet years getting wetted and dry years getting drier, a trend that is predicted to intensify with further global warming. Erratic rainfall undermines recharge of aquifers and reservoirs.
- ***Groundwater Overextraction****:* Farmers increasingly pump groundwater to cope with rainfall uncertainty, leading to falling water tables in regions such as Punjab, India, and the North China Plain. Climate change significantly worsens groundwater overextraction in India by raising temperatures, which intensifies the need for irrigation, leading to increased pumping despite reduced recharge from erratic monsoons. Warming increases the rate of groundwater depletion, potentially tripling it in some areas by 2080, with this multi-dimensional crisis threatening India's food and water security. The crisis is exacerbated by India's heavy reliance on groundwater for irrigation, with high rates of overuse already prevalent in several key agricultural states due to increased irrigation demand resulting intensified pumping, reduced recharge and amplified depletion.
- ***Glacial Melt and River Flows:*** Glacial melt increases climate change vulnerability by first elevating river flows and flooding risks, followed by severe water shortages, increased

variability, and greater flood and landslide potential as glaciers shrink and eventually disappear. The decline in these crucial water stores, particularly from the Himalayas, threatens water security, agriculture, and hydropower for the billion people reliant on affected river systems. In India, glacier retreat threatens the long-term flow of rivers like the Indus and Ganges, which sustain millions of farmers.

- ***Salinization and Waterlogging:*** Saline soils are widespread in India, covering an estimated 2.95 million hectares across 16 states, with significant areas in coastal regions and the Indo-Gangetic Plains. Gujarat, Andhra Pradesh, Rajasthan, Haryana, and Uttar Pradesh are particularly affected, due to factors like sea tides, a higher water table, and improper irrigation practices that lead to waterlogging and salt build-up, rendering vast areas unproductive. Rising sea levels, floods, and poor irrigation management contribute to soil salinity and waterlogging. Saline water intrusion in coastal areas reduces soil productivity.
- ***Climate-induced Nutrient Imbalances:*** Changes in rainfall and temperature alter soil microbial activity and nutrient cycles. Higher rainfall intensity causes leaching of nitrogen and phosphorus, reducing nutrient availability. Warmer conditions accelerate organic matter decomposition, leading to long-term declines in soil carbon stocks. These imbalances directly affect the efficiency of fertilizers and crop productivity.

9. Mitigation and Adaptation Strategies

Climate-Resilient Agriculture (CRA) refers to approaches, practices, and systems designed to sustain agricultural productivity, protect ecosystems, and strengthen food security under conditions of increasing climate variability and uncertainty. Climate change increasingly exposes agricultural systems and food security to multiple uncertainties- in temperature, precipitation, extreme events, pests, and market dynamics. CRA strategies emphasize adaptation while integrating mitigation and socio-economic resilience. Herein, we synthesize mitigation and adaptation strategies relevant to agricultural systems under climatic uncertainty.

10. Crop production strategies related to climate uncertainty

The importance of crop production-related strategies under climate uncertainty lies in ensuring stable yields, maintaining soil fertility, and safeguarding food security despite unpredictable weather patterns. Farmers need to adopt climate-resilient varieties that can withstand drought, floods, and heat stress while diversifying crops to reduce risks from single-crop failure. Efficient water management practices such as rainwater harvesting, micro-irrigation, and conservation tillage are crucial to cope with erratic rainfall. Integrating nutrient management, agroforestry, and soil health restoration helps in sustaining productivity under changing climatic conditions. The use of digital tools, early warning systems, and climate-smart advisories enables timely decisions for sowing, irrigation, and harvesting. Altogether, these strategies are essential to build resilience, reduce vulnerability, and ensure sustainable crop production in the face of climate uncertainty**.** Box 1 highlights crop production strategies related to climate uncertainty.

Box 1. Crop Production Strategies Related to Climate Uncertainty

- Develop crop varieties tolerant to biotic and abiotic stresses and increased productivity.
- Promote drought-resistant, flood-tolerant, and heat-resilient crop varieties.
- Promote diversity, local knowledge, and low-external-input strategies that often yield resilience under uncertainty.
- Decrease rice and wheat areas with suitable crops and cropping systems to protect natural resources.
- Promote pulses for food, nutrition and environmental security and to arrest import of this commodity.
- Encourage diversified cropping systems, integrated farming, and conservation agriculture.
- Expand micro-irrigation, rainwater harvesting, and watershed management.
- Improve soil health through smart fertilizers, specialty fertilizers, organic amendments, biofertilizers, and precision nutrient management.
- Reduces vulnerability to pest outbreaks that may shift with climate through
- integrated pest and disease management (IPM)
- Deploy ICT tools, AI, and remote sensing for climate forecasting and early warning systems.
- Scale precision farming, sensor-based irrigation, and digital advisories to farmers.
- Strengthen crop and livestock insurance schemes with faster claim settlements.
- Expand weather-indexed insurance and risk-sharing mechanisms.
- Train farmers in adaptive practices and sustainable resource use.
- Strengthen extension services, farmer field schools, and community-based adaptation models.
- Promote new agricultural implements to facilitate line sowing, raised bed planting, placement of fertilisers, residue recycling, harvesting and threshing, shelling etc. to ensure adoption of fertilizer best management practices and also to minimize cost of cultivation.
- Electrification and efficient motors, combined with renewable energy (solar pumps, biogas), reduce on-farm fossil fuel use and emissions from post-harvest losses.

11. Nutrient best management practices related to climate uncertainty

Correcting nutrient use in climate uncertainty requires a shift from generalized fertilizer application toward adaptive, precise, and resilient nutrient management practices. The adoption of the 4R nutrient stewardship principle-using the right source, at the right rate, at the right time, and in the right place-becomes essential to reduce nutrient losses caused by erratic rainfall, drought, or sudden temperature variations. Integrated nutrient management, which combines chemical fertilizers with organic manures, compost, biofertilizers, and nanofertilizers, enhances soil fertility and improves nutrient-use efficiency under uncertain climate conditions. **Box 2** presents a summary of the fertilizer best management practices related to climate uncertainty.

Box 2. Fertilizer Best Management Practices Related to Climate Uncertainty

- Promote precision fertilization and site-specific nutrient management to reduce N_2O emissions by matching application rates and timing to crop needs. Techniques include split application, use of nitrification inhibitors, and variable-rate technology.
- Promote enhanced-efficiency fertilizers (EEFs***).*** Slow-release, coated fertilizers, stabilized nitrogen formulations, IFFCO Nanofertilizers and water-soluble fertilizers reduce volatilization and leaching. Co-benefits are improved nutrient-use efficiency, lower input costs (potentially), reduced water contamination and protection of environment.
- Flexible nutrient management is important considerations under uncertainty that responds to intra-seasonal weather (e.g., delaying top-dressings under drought) reduces risk of inefficiency during abnormal seasons.
- Promote soil carbon sequestration and conservation agriculture. Conservation tillage/no-till and residue retention increase soil organic carbon, enhance water infiltration and resilience to drought, and potentially reduce fuel use.
- Promote Cover cropping and crop rotations. Maintaining continuous soil cover build organic matter and break pest cycles.
- Agroforestry systems integrate trees with crops/livestock, providing carbon sinks, shade (reducing heat stress), windbreaks, and additional income streams (fruit, timber). Perennial systems (e.g., improved forages, perennial grains) increase carbon storage and system stability.
- Proper manure management is important to ensure availability of quality compost and FYM particularly under climate uncertainty scenario. Anaerobic digestion, composting, and improved storage reduce CH_4 and N_2O and produce renewable energy.

12. Water management related strategies in climate uncertainty

Water management strategies in climate uncertainty focus on conserving, harvesting, and efficiently using water to cope with erratic rainfall and drought. Water management strategies in climate uncertainty focus on conserving, harvesting, and efficiently using water to cope with erratic rainfall and drought. Key approaches include rainwater harvesting, micro-irrigation like drip and sprinkler systems, use of drought-tolerant crops, groundwater recharge, and adoption of conservation practices such as mulching and zero tillage to reduce evaporation losses. Smart irrigation scheduling using weather forecasts and digital tools ensures water is applied at the right time and in the right amount, making agriculture more resilient to climate variability. Herein a summary of water management strategies related to climate uncertainty is provided in **Box 3**.

Box 3. Water Management Strategies Related to Climate Uncertainty

- Expand **micro irrigation and fertigation**. Efficient irrigation (drip, micro-sprinklers) and scheduling reduce water use and increase resilience to short-term water shortages.
- Manage **aquifer recharge and rainwater harvesting** to create buffer against intra-seasonal variability.
- Ensure **improved conveyance of water** and reduced losses prevent water wastage that exacerbates vulnerability during dry spells.
- Promote **dry direct-seeding** technology and optimize rice variety selection to reduce methane emissions.
- Scale up **low-or no tillage farming** to minimize soil disturbance.
- Expand **conservation agriculture** to improve rice and wheat straw management by incorporating crop residues.
- Expand **reclamation and management of problem soils** for amelioration of problem soils such as acid and alkali soils, hilly and slopy lands, eroded and ravenous lands through soil conservation and erosion control measures.
- Promote **water conservation** through rain water harvesting, field bunding, summer ploughing, mulching and efficient use of water in both irrigated and rainfed farming systems.
- Improve **water management** to reduce methane emissions in rice paddies and also salinity.
- **Promote Scheduling and precision irrigation.** Use soil moisture sensors and climate advisories to avoid water stress.

13. Technology and tools (digital platforms, remote sensing, and artificial intelligence) to combat climate uncertainty

The importance of technology and tools such as digital platforms, remote sensing, and artificial intelligence in climate services lies in their ability to provide timely, accurate, and location-specific information for managing climate risks in agriculture. Digital advisory systems and mobile applications deliver weather forecasts, crop advisories, and early warning alerts directly to farmers, enabling informed decisions on sowing, irrigation, fertilizer use, and pest management. Remote sensing through satellites and drones helps in monitoring soil moisture, crop health, drought severity, and flood risks, supporting proactive resource management. Artificial intelligence further enhances climate services by analysing large datasets, predicting extreme events, and generating site-specific recommendations tailored to local conditions. Together, these technologies strengthen adaptive capacity, reduce vulnerability, and improve resilience of farming systems under climate uncertainty.

14. Benefits and scale of application of climate-resilient agriculture strategies

Climate-resilient agriculture strategies play a crucial role in minimizing risks and sustaining productivity in the face of climate uncertainty. Their primary benefit lies in stabilizing crop yields by reducing the adverse effects of drought, floods, heat stress, and other climate-induced shocks. By adopting resilient crop varieties, conservation practices, and resource-efficient technologies, farmers can maintain production even under unfavourable conditions. These strategies also contribute significantly to conserving natural resources such as soil and water, which are increasingly threatened by unpredictable rainfall and extreme weather. Improved soil health through integrated nutrient management, organic matter addition, and agroforestry enhances the capacity of soils to store water and nutrients, making farming systems more sustainable in the long term. In addition, climate-resilient approaches promote efficient use of inputs such as water, fertilizers, and energy, which not only reduce costs for farmers but also lower greenhouse gas emissions, thereby contributing to mitigation of climate change.

The benefits extend beyond productivity and resource conservation to strengthening farmers' livelihoods and food security. Stable yields translate into more consistent incomes, which protect smallholders from falling into poverty during climate shocks. Resilient practices also encourage diversification of crops and livelihoods, reducing dependence on a single source of income and spreading risks across multiple enterprises. Moreover, the use of digital technologies, climate advisories, and remote sensing tools enhances farmers' ability to make timely decisions, further improving their adaptive capacity. At a broader scale, climate-resilient agriculture contributes to national food security, rural development, and achievement of sustainable development goals.

In terms of scale of application, these strategies can be implemented at multiple levels. At the farm level, practices such as crop diversification, micro-irrigation, mulching, and improved crop varieties can directly reduce risks. At the community and watershed level, collective water harvesting, soil conservation, and agroforestry projects create shared resilience. At the regional and national level, policy support, infrastructure development, and climate information services expand the reach and impact of these strategies. The integration of climate-resilient practices into government programs, private sector initiatives, and international development projects ensures widespread adoption and scalability. Digital tools and artificial intelligence further enhance the scaling process by enabling rapid dissemination of climate advisories, monitoring of resource use, and delivery of customized recommendations to millions of farmers.

15. Future Action Plan

- Promoting the development and adoption of climate-resilient crop varieties that can withstand drought, floods, salinity, and heat stress to ensure stable yields under uncertain conditions.
- Strengthening integrated water management through rainwater harvesting, micro-irrigation, groundwater recharge, and efficient irrigation scheduling to cope with erratic rainfall and water scarcity.
- Enhancing soil health by promoting integrated nutrient management, use of organic manures, biofertilizers, and nanofertilizers, along with conservation agriculture practices to sustain long-term productivity.
- Expanding digital climate services, remote sensing, and artificial intelligence-based tools to deliver timely advisories, weather forecasts, and early warnings to farmers for informed decision-making.
- Supporting diversification of crops, farming systems, and livelihoods including agroforestry, allied activities, and resilient value chains to reduce risks from climate shocks and stabilize farm incomes.
- Strengthening institutional support through policies, credit, insurance, and capacity-building programs that encourage adoption of climate-smart practices at scale.

- Encouraging community-based approaches such as watershed management, farmer producer organizations, and collective resource management for building resilience at local and regional levels.

Conclusion

Agriculture is at the frontline of climate uncertainty. Erratic rainfall, prolonged droughts, floods, and shifting pest and disease dynamics are destabilizing crop and livestock systems worldwide. Food security is at risk through declining yields, price volatility, post-harvest losses, and nutritional deficiencies. Vulnerable groups- particularly smallholders, women, and landless laborers-are disproportionately affected, threatening equity and social stability. Managing agriculture in the age of climate uncertainty requires a ***systemic shift***: from reactive disaster responses to proactive, integrated strategies. The climate-resilient agriculture strategies help stabilizing yields, conserving resources, improving soil and water health, enhancing food security, and securing farmer incomes, while their scale of application ranges from individual farms to global agricultural systems. By aligning science, technology, policy, and community participation, these strategies offer a pathway toward sustainable and adaptive agriculture under climate uncertainty. Policymakers must align ***agriculture, climate, and food security agendas***, create enabling institutions, and ensure financing reaches the most vulnerable. Only through this multi-level, inclusive approach can we secure resilient food systems and safeguard livelihoods in an increasingly uncertain climate future.

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AGROFORESTRY FOR SUSTAINABLE DEVELOPMENT: A SYNERGISTIC APPROACH TO CLIMATE RESILIENCE, FOOD SECURITY AND BIODIVERSITY CONSERVATION

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Abstract
Agroforestry is a smart way of farming where trees are grown with crops and sometimes animals. Unlike traditional farming, which often harms soil and wildlife, this method improves the land and benefits farmers. In dry areas, it can boost harvests by 20–50%. Trees also absorb carbon dioxide, helping fight climate change. For example, in Africa, Faidherbia albida trees enrich the soil and help crops survive drought. Agroforestry supports birds, bees, and other wildlife, while preventing erosion and keeping soil fertile. Farmers earn more by growing fruits, timber, or medicinal plants alongside crops, ensuring income year-round. Though trees take time to grow, support like carbon credits, government schemes, and eco-friendly markets can encourage wider adoption.

Keywords: Agroforestry Systems, Biodiversity Conservation, Climate Resilience, Food Security, Sustainable Development

Introduction
Agroforestry is a farming practice that integrates trees with crops and sometimes livestock, offering a more sustainable alternative to conventional monocultures that often degrade soil, reduce biodiversity, and increase greenhouse gas emissions. According to the World Agroforestry Centre (ICRAF, 2023), these systems can capture 2–10 tons of CO_2 per hectare annually, making them valuable for climate change mitigation. A major strength of agroforestry is its contribution to food security. The Food and Agriculture Organization (FAO, 2023) reports yield increases of 20–50% in drought-prone regions, as trees improve soil fertility and retain water. In sub-Saharan Africa, *Faidherbia albida* supports staple crops during dry spells, while shade-grown coffee systems in Central America improve bean quality and provide additional income from timber and fruits (Perfecto *et al.*, 1996; Moguel & Toledo, 1999). This diversification reduces market risks and ensures year-round food and income.

Agroforestry also enhances biodiversity. Shade-grown systems support pollinators, birds, and other wildlife, with some farms hosting up to 80% of forest bird species (Philpott *et al.*, 2008). Diversified farms may sustain 40–90% more biodiversity than monocultures (Science Advances, 2023). Cocoa agroforests in West Africa, for example, protect habitats for migratory birds and safeguard genetic resources critical for climate resilience. Large-scale success stories highlight its impact. In Niger, the

Farmer-Managed Natural Regeneration (FMNR) movement restored 5 million hectares of degraded land at low cost (WRI, 2023). In Southeast Asia, rubber-based systems intercropped with fruits and spices have tripled farmer incomes while reducing deforestation. Agroforestry directly advances SDGs on poverty reduction, food security, climate action, and biodiversity. However, adoption faces challenges, as trees take years to yield returns. Solutions include carbon credits, payment for ecosystem services, and supportive policies like India's National Agroforestry Policy (2014). Recognized under the UN Decade on Ecosystem Restoration, agroforestry could restore 350 million hectares globally by 2030.

1. Agroforestry

Agroforestry as a sustainable management system for land that increase overall production, combines agriculture crops, forest plants, tree crops and applies animals simultaneously or sequentially and applies management practices that are compatible with the cultural patterns of a local population (Bene *et al*., 1977). Agroforestry is a farming approach that integrates trees into agricultural landscapes, combining the benefits of forestry and agriculture. By growing multiple crops together, including trees, farmers can create diverse, resilient ecosystems that mimic natural forests. Indian agriculture faces diverse challenges and constraint due to growing demographic pressure, increasing food, feed and fodder needs, natural resource degradation and climate change (Dhyani *et al.* 2013) therefore a management system needs to be devised that is capable of producing food from marginal agricultural land and is also capable of maintaining and improving quality of producing environment (Dobriyal, 2014).

2. Benefits of Agroforestry

2.1 Climate Resilience

Agroforestry plays a key role in building climate resilience by combining trees with crops to protect farms and ecosystems. Trees act as natural buffers against extreme weather, helping farmers adapt to droughts, floods, and heatwaves. Research shows that agroforestry systems can capture 2–10 tons of carbon dioxide per hectare annually while reducing soil erosion by up to 90% during heavy rains (IPCC, 2022; FAO, 2021). Shade from trees lowers ground temperatures, reduces evaporation, and creates stable microclimates that protect crops from heat stress (Nature Climate Change, 2020). The latest IPCC report highlights the urgent need to cut global CO_2 emissions by 45% by 2030 and reach net-zero by 2050 (IPCC, 2023). Trees contribute to this by locking carbon in their trunks, branches, and roots for decades (Nowak *et al*., 2022; Pan *et al*., 2011). Agroforestry and reforestation are thus vital natural climate solutions, bridging the gap toward global climate goals while supporting biodiversity (Griscom *et al*., 2017).

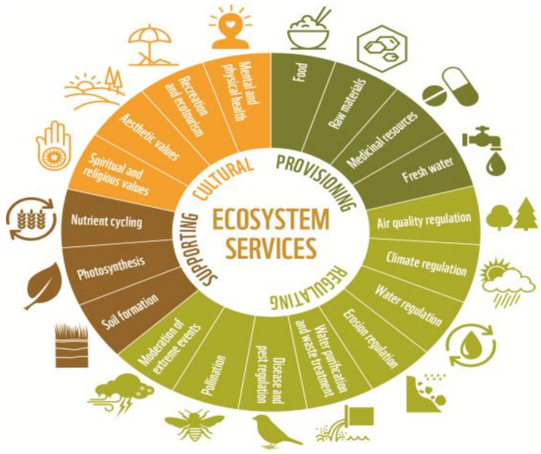

Fig. 1 Different types ecosystem services provided by Agroforestry

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2.2 Food Security

Agroforestry offers an effective way to strengthen global food security by creating productive and resilient farming systems. Integrating trees with crops reduces heat stress on plants by 2–4°C while enriching soils through nutrient cycling and organic matter (UNEP, 2023; Coe *et al*., 2023). A recent meta-analysis found that agroforestry increases crop yields by an average of 38%, with the greatest benefits in drought-prone areas where tree roots retain soil moisture (Bayala *et al*., 2023). These systems also support ecological services. They reduce pest damage by 40–60% and host up to three times more pollinator species than monocultures (Pumarino *et al*., 2023; Klein *et al*., 2022). Importantly, agroforestry ensures continuous food supply: studies show such farms provide food for 11 months annually compared to 6 months under conventional farming (Jamnadass *et al*., 2023).

2.3 Biodiversity Conservation and Benefits

Agroforestry systems play a critical role in conserving biodiversity by creating diverse habitats that support plants, animals, birds, insects, and microorganisms. Their multi-layered structure trees, shrubs, and crops provides food, shelter, and nesting sites, fostering ecological balance (Jose *et al*., 2021; Díaz *et al*., IPBES 2019). Research shows agroforestry landscapes host 40–90% more wildlife than monocultures, including essential pollinators such as bees and birds (Kremen & Merenlender, 2020). They also conserve genetic resources, helping protect sensitive and endangered species and maintaining crop and wild plant diversity vital for climate resilience (Dawson *et al*., 2023). By mimicking natural ecosystems, agroforestry reduces pressure on forests, slowing deforestation and supporting native species (Nature Sustainability, 2023; Perfecto & Vandermeer, 2023). Shade-grown coffee systems, for example, preserve up to 80% of native bird species compared to sun-grown fields (Perfecto & Vandermeer, 2023). Such biodiversity delivers essential services natural pest control cuts pesticide use by 30–50% (Tscharntke *et al*., 2022), while nutrient-rich leaf litter improves soil fertility (Udawatta & Jose, 2021).

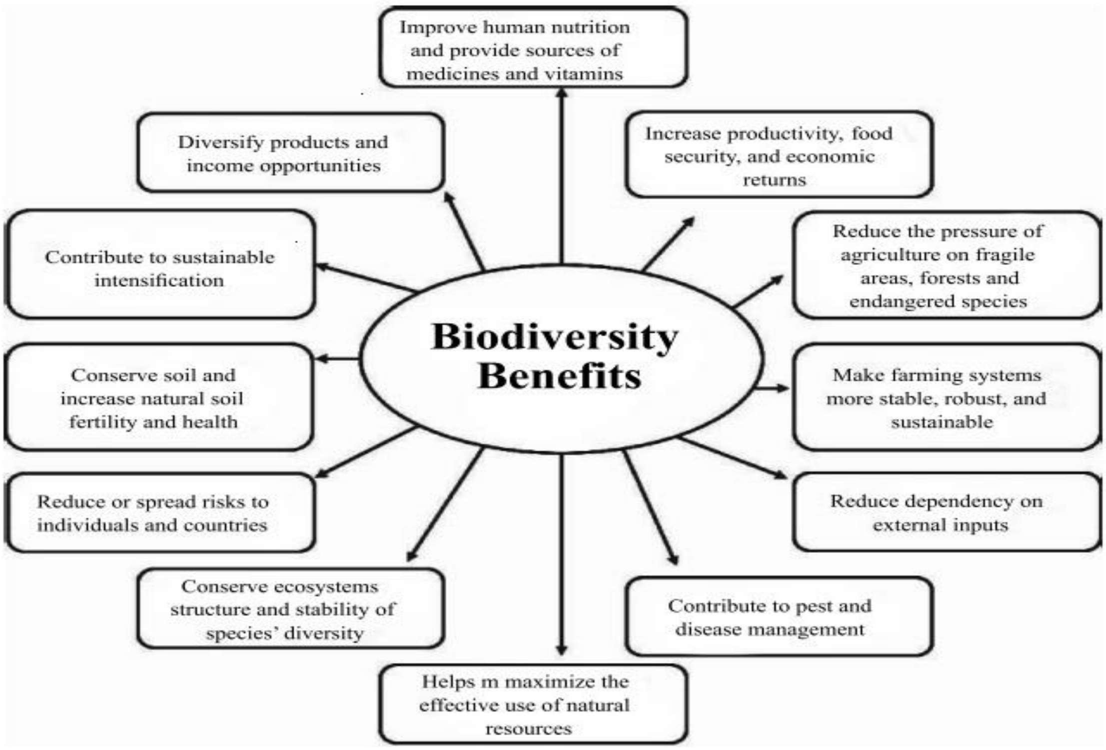

Fig.2 Different types of Biodiversity benefits provided by Agroforestry

2.4 Soil Health

Agroforestry improves soil fertility and structure through nitrogen fixation, organic matter inputs, and erosion control. Nitrogen-fixing trees like *Leucaena* and *Gliricidia* convert atmospheric nitrogen into usable forms, reducing reliance on chemical fertilizers (Sileshi *et al*., 2014). Non-fixing trees add organic matter through leaf litter and root activity, enhancing soil structure and water retention (Jose, 2009). Tree roots stabilize soil, cutting erosion by up to 90% (Lal, 2020). Increased organic matter supports microbes that boost nutrient cycling (Udawatta & Jose, 2021).

2.5 Livelihoods

Agroforestry strengthens rural livelihoods by diversifying income and improving resilience. Farmers practicing it earn 30–50% more than those in monocultures, as they sell fruits, nuts, timber, latex, and medicinal plants (World Agroforestry Centre, 2023). In Indonesia, rubber agroforestry provides steady latex income, while intercropped fruits and spices add seasonal earnings (Santoso *et al*., 2022). This diversity cushions farmers from price fluctuations (Dawson *et al*., 2021). Women gain particular benefits through products like shea nuts and medicinal plants (FAO, 2023).

3. Agroforestry Systems

Agroforestry includes diverse systems adapted to local needs. Alley cropping grows crops between tree rows, improving soil fertility and reducing erosion (Thevathasan & Gordon, 2004). Silvopasture integrates trees, forage, and livestock, offering shade and carbon storage (Nair *et al*., 2021). Windbreaks shield crops from wind and create favorable microclimates (Brandle *et al*., 2004). Forest farming produces shade-loving crops such as ginseng under tree cover (Chamberlain *et al*., 2022), while homegardens in tropical regions mix fruits, vegetables, and medicinal plants for food and income (Kumar & Nair, 2006). A strong example is the Eucalyptus–wheat agrisilviculture system, which reduces wind erosion by 40–60% and lowers crop water stress through canopy effects (Jose *et al*., 2023). It supports 30% more arthropod diversity, including pollinators and pest controllers (Singh *et al*., 2022), while boosting wheat yields by 15–20% through better soil moisture (ICRAF, 2023). Proper spacing allows timber income with minimal competition, sequestering 2–4 tons of carbon per hectare annually (Dhyani *et al*., 2021; FAO, 2023).

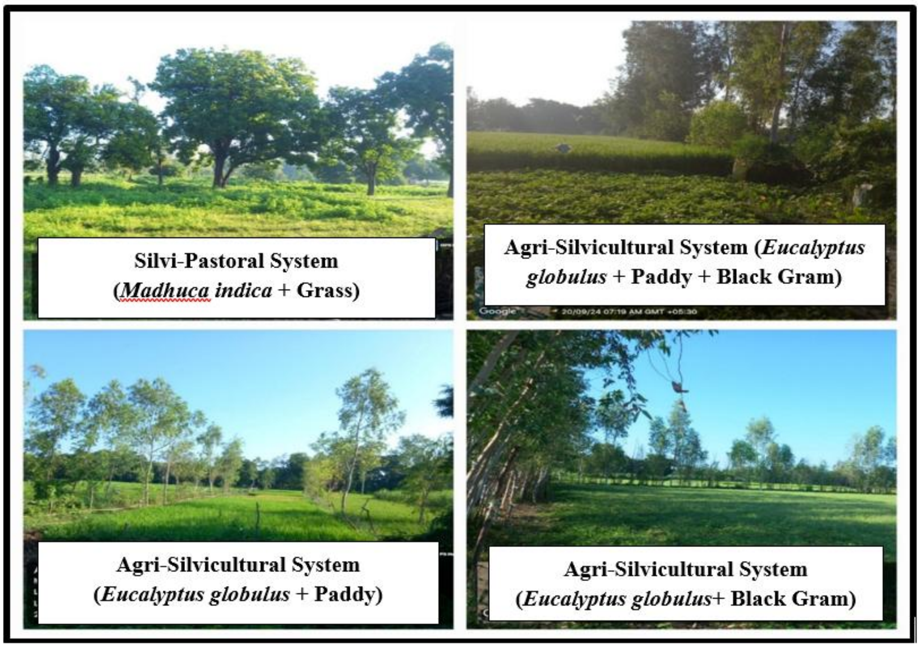

Fig. 3 Different types of Agroforestry Systems

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4. Agroforestry's Contribution to Sustainable Development Goals (SDGs)

Agroforestry offers an integrated pathway to achieving multiple Sustainable Development Goals (SDGs). By diversifying income from timber, fruits, and non-timber products, it supports SDG 1 (No Poverty), with households earning 30–50% more than those practicing monoculture (World Bank, 2023). Improved crop yields and dietary diversity strengthen SDG 2 (Zero Hunger), as studies show 20–40% greater food availability in agroforestry households (FAO, 2023). Through carbon sequestration of 2–10 t CO_2/ha/year and greater resilience to droughts and floods, agroforestry directly contributes to SDG 13 (Climate Action) (IPCC, 2022). Equally, these systems conserve 40–90% of natural biodiversity, reducing deforestation pressures by 35–60% in frontier regions, advancing SDG 15 (Life on Land) (Nature Sustainability, 2023) reecognized under the UN Decade on Ecosystem Restoration (2021–2030).

Conclusion

Agroforestry is a sustainable land-use system that integrates trees with crops and livestock to improve both livelihoods and the environment. By enhancing soil fertility, preventing erosion, and storing carbon, it strengthens climate resilience and helps farms withstand droughts and floods. These systems diversify income through fruits, nuts, timber, and other products, improving rural livelihoods. Globally, farmers report healthier soils, higher yields, and more stable farms under agroforestry practices. To scale its benefits, supportive policies, fair market access, and farmer incentives are essential, making agroforestry a vital strategy for food security, poverty reduction, and biodiversity conservation.

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FISH PROTEIN ICE CREAM: A SAFE AND NUTRITIOUS FUNCTIONAL DESSERT

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Abstract
The incorporation of fish proteins into ice cream presents a novel opportunity to combine nutritional enhancement with consumer indulgence. Fish proteins provide high biological value, essential amino acids-particularly omega-3 fatty acids-and bioactive peptides with potential health benefits. However, their application in frozen desserts raises critical considerations regarding food safety and consumer acceptance. This article reviews the nutritional benefits of fish protein ice cream and explores its safety and sensory attributes. Balancing these factors will determine the feasibility and market success of fish protein ice cream as a functional food innovation.

Keywords : Fish protein; Ice cream; Dessert; Nutritional benefits; Innovation

Introduction

Ice cream is the most widely consumed frozen dairy dessert, but the category also includes frozen custard, frozen yogurt, sherbet, and frozen milkshakes and smoothies (Goff *et al*., 2025). Frozen desserts are valued for their creamy texture due to high fat content, but excessive consumption is linked to obesity, diabetes, and cardiovascular disease (Tang *et al*., 2025). Fish processing generates large amounts of scales, skin, and bones, which can be used to produce gelatin. Gelatin plays vital roles in confectionery by stabilizing foam, binding, emulsifying, and controlling sugar crystallization. In dairy products, it prevents whey separation, improves texture, and enhances foam formation in milk-based desserts. In ice cream, gelatin modifies ice crystal size and distribution, improving mouthfeel and texture (Joy *et al*., 2024). Fish skin gelatin hydrolysate served as a stabilizer and emulsifier in the ice cream production (Tekle *et al*., 2025). Gelatin from channel catfish (*Ictalurus punctatus*) skin was successfully incorporated into ice cream, resulting in improved mouthfeel and a thicker, smoother texture (Duan *et al*., 2018). Replacing the emulsifier with 0.25 g gelatin hydrolysate alongside 0.75 g sahlep increased ice cream protein content and achieved the highest sensory scores while preserving rheological and structural properties (Tekle *et al*., 2025).

Nutritional Benefits of Fish Protein in Ice Cream

The fortification of foods with marine-derived ingredients such as omega-3 fatty acids and fish proteins, particularly in products like ice cream, bread, milk, and yogurt, represents a promising strategy to enhance nutritional quality (Okubanjo *et al*., 2025). Ice cream fortified with microencapsulated silver carp oil could be an effective way to deliver PUFA while enhancing its nutritional and functional value. Such fortification represents a novel approach to developing functional desserts with added health benefits (Nawas *et al*., 2017). Gelatin is a valuable protein source, free from cholesterol, sugar, and fat. It is fully digestible and contributes to nutrition by enhancing protein intake, lowering carbohydrates, salt, and fat in low-fat foods, and serving as a carrier for vitamins (Joy *et al*., 2024). Fish gelatin was incorporated into ice cream as a protein enhancer and texture modifier. Its addition increased the protein and fiber content of the product, indicating its potential for developing nutritionally rich, low-fat ice cream (Mada Hatsa *et al*., 2024). Protein quality in ice cream improves flavor, foaming, and water-holding capacity, affecting texture and viscosity, with 0.7% milkfish scale gelatin showing optimal results (Swastawati, *et al*., 2022).

Different fish protein sources have been explored to enhance the nutritional and functional properties of ice cream. Fish skin gelatin, derived from species such as Nile tilapia, channel catfish, or sea bream, is widely used as a stabilizer, emulsifier, and texture enhancer due to its high protein content and gelling properties. Each source offers unique functional and sensory effects, and optimal formulations require balancing nutritional enrichment with taste, texture, and consumer acceptability (see Table 1).

Table1. Different fish protein sources in Ice cream

Sl. N.	Fish protein source	Benefits in Ice cream	References
1.	Channel catfish (*Ictalurus punctatus*) fish skin gelatin	- Gelatin was extracted from the skin of channel catfish. SDS-PAGE patterns showed that channel catfish gelatin contained more high-molecular-weight components than calf bone gelatin. - It also exhibited superior foaming capacity, foaming stability, and emulsion stability. - When applied in ice cream, channel catfish gelatin provided a good mouthfeel. - These results indicate its strong potential for utilization in the food industry.	Duan *et al*., 2018
2.	Fish skin gelatin	- Fish skin gelatin is widely used as a stabilizer in ice cream. - Sensory evaluation indicated that the addition of 0.1% fish gelatin resulted in a softer texture preferred by panelists. - The optimized formulation exhibited 30.63% overrun, 40.77% total solids, and a melting rate of 197 s/g.	Ayudiarti and Oktavia, 2020
3.	Spanish mackerel (*Scomberomorus commerson*) fish bone gelatin	- Mackerel fish bones are rich in protein used as a raw material for gelatin. - Increasing gelatin concentration in ice cream showed a strong correlation with overrum (r = 0.94), melting resistance (r = 0.911), and viscosity (r = 0.995). - Organoleptic tests revealed that higher concentrations improved panelists' preference for softness but reduced acceptance of color, flavor, and aftertaste.	Rahimah *et al*., 2020
4.	Nile tilapia *(Oreochromis*	- Fish skin gelatin enhanced protein and fiber in ice cream, showed minimal microbial growth during	Mada Hatsa *et al*., 2024

Sl. N.	Fish protein source	Benefits in Ice cream	References
	niloticus) fish skin gelatin	the first week, and can be used to make nutritionally rich, low-fat ice cream.	
5.	Sea bream (*Sparus aurata*) fish skin gelatin hydrolysate	- Gelatin hydrolysate derived from fish skin waste can be effectively utilized as a natural emulsifier and stabilizer in ice cream, significantly increasing protein content. - It shows strong potential as a sustainable and functional ingredient, offering both technological benefits and value-added utilization of seafood by-products.	Tekle *et al.*, 2025

Safety Considerations

Microbial growth is a critical concern when incorporating fish-derived ingredients into ice cream. In a recent study, Mada Hatsa et al. (2024) reported that *Escherichia coli*, *Staphylococcus aureus*, *Salmonella*, and *Shigella* were not detected during the first week of storage in fish gelatin-fortified ice cream. However, an increase in total bacterial counts and the presence of *Staphylococcus aureus* were observed in subsequent storage periods. These findings suggest that while fish gelatin can be effectively utilized to develop nutritionally enriched, low-fat ice cream with acceptable microbiological stability, careful monitoring of storage conditions and shelf-life is essential to ensure consumer safety.

Consumer Acceptance and Sensory Optimization

Ice cream is a dairy-based product known for its nutritional value. Mackerel fish bones serve as a sustainable raw material for gelatin production due to their high protein content. Increasing the concentration of gelatin improves the softness of ice cream, which in turn makes it more preferred by panelists (Souvia *et al*., 2020). Appearance is a key factor in consumer preference, with visually appealing ice cream perceived to have superior taste and quality. The composition of ingredients, particularly fat content, affects flavor, texture, and melting behavior. Ice cream aroma affects its delicacy, and higher milk content lessens the aroma of milkfish scale gelatin. Ice cream containing 0.7% milkfish scale gelatin received the highest ratings for appearance, colour, flavor, and aroma, and overall sensory qualities, indicating that 0.7% is the optimal concentration. Prepared according to Indonesian National Standard 01-3713-1995, milkfish scale gelatin shows potential as a stabilizer in ice cream production (Swastawati, *et al*., 2022).

Conclusion

Fish protein ice cream represents a novel functional food that combines consumer indulgence with health benefits. Its successful development depends on carefully balancing nutritional enhancement, food safety, and sensory quality, ensuring that the product is both health-promoting and palatable. Incorporating fish proteins introduces challenges such as microbial contamination, and off-flavors, which can be mitigated through optimized processing techniques and protein modification. Consumer acceptance studies are also essential to evaluate flavor, texture, and overall palatability, thereby realizing the product's commercial and nutritional potential.

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BEYOND CROPS: JAMMU'S RISE AS A VEGETABLE SEED CAPITAL

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Most of us, when we think of agriculture in Jammu, think of wheat, maize, or basmati rice growing in fields that sway in the breeze. But there is a silent revolution growing in Jammu, going beyond crops into the small yet big world of vegetable seeds. With a little bit of momentum, Jammu can become a leading player in India's seed industry, increasing farmer incomes, rural jobs, and reducing dependence on imports of high-value hybrids. This article sets out to discuss the importance, constraints, and prospects of vegetable seed production in Jammu.

Now, a question arises: why is the quality of vegetable seeds so important?
It all comes back to a seed. The vegetable seed may seem small and basic, but it is a vessel of opportunity. For a farmer, the seed is not just a part of the crop, but a part of their future. While land in Jammu is plentiful, it faces significant barriers that using the right vegetable seed could determine what type of season they will have. Good seeds are reliable partners. They germinate at the same time, grow uniformly strong, and produce healthy, uniform vegetables which customers want. When a farmer sows quality seed, they are assured that most of the plants will grow together at a similar pace, which allows them to manage the field better and simplifies the harvest. Stop and think about it, poor seed means poor control, different sizes of plants, and when the weather changes, some plants experience a period of stress, which continues to be detrimental from watering to harvesting to selling. There is also a certain amount of peace of mind using the seed that has reduced factors for plant pests and diseases. We live in an area with unpredictable weather and a few sunny days, easily result in an unexpected shower, and this change usually results in pest problems or fungal infections. But good-quality seeds often come with built-in protection, which means fewer pesticides, lower costs, and safer, cleaner vegetables reaching our kitchens.

And let's not overlook the fact that appearance is also important. Consumers in today's markets want shiny, fresh, and picture-perfect vegetables. Good seed grows produce that has consistency - size, shape, and colour, whether it is a bright green capsicum or a deep red tomato. Uniformity and good-looking produce is good to the eye, but also sells at better prices. Good seed is also bred for the effects of climate change, whether that is extreme temperature or humidity, short droughts, or excessive rain. We live in an uncertain time when growing is becoming more and more of a risk every year; having the confidence that ground or crops that can survive and produce gives farmers hope. These crops also last longer post-harvest, which is of no small consequence if a farmer is selling from rural areas to city markets. Yes, good seed costs more up front, but scientific evidence shows that it always recoups that cost and more. Many Jammu farmers who have adopted premium seed all say their income increased, reduced crop loss, and lower stress levels. Farmers in districts like Kathua, Samba, and Udhampur have seen significant increases in yield and market value by transitioning from traditional to certified vegetable seeds. A 2022 evaluation report prepared for SKUAST-Jammu (November 2022) evaluated the impact of certified hybrid seed adoption in capsicum, brinjal, and tomatoes and found approximately 25–35% increases in yield, as well as a decrease in the use of plant protection chemicals. These increases contribute to not only improved yields, but also improved profitability and decreased risk of production, especially for small and marginal farmers in the Jammu plains. In the final analysis, a seed is more than just the beginning of a crop cycle. A seed represents trust- trust in nature, in science, trust in future outcomes. For vegetable farmers in Jammu, investing in the right seed is not just a smart agricultural practice or strategy; it's simply smart lives.

A good seed means a great start

The average yield of vegetables in Jammu, as per the SKUAST-Jammu Package of Practices for Vegetable Crops (2020) is 22.1 MT/ha, which is much higher than the national average of 17.6 MT/ ha; this is due to the use of quality seeds and improved practices.

Existing Constraints to Vegetable Seeds Production in Jammu Region

While the farmers in the region of Jammu have become more cognisant of the importance of good seeds, the production of these seeds locally is challenging. The Jammu region lacks significant infrastructure, as it currently has no seed processing units, cold storage facilities to store seeds, and no certified seed production units, and many farmers cannot reach these services because of travel restrictions. Because of this, the farmers are usually forced to buy seeds outside of Jammu, oftentimes not even knowing if they are genuine.

Another existing constraint is the lack of practical experience or training regarding the relationship in field production. Seed production has specific methods that do not exist on standard farms, including maintaining isolation distances between species, rouging out undesired plant types, and harvesting appropriately. jumped to produce seeds. Unfortunately, many have not received training on these techniques. Farmers will not undertake seed production unless they receive support from agricultural officers or agricultural experts or inputs from institutions; even if they want to experiment with seed production, they lack the confidence to try the process without guidance.

Then there's the climate issue. Jammu's climate can be irregular; it can rain when it shouldn't rain, and the heat can come too early. These irregularities can disrupt flowering and pollination, two important developmental steps of the seed. A few days of stress can mean poor seed quality or severely limited quantity in crops like tomato, capsicum and cucurbits. The economic picture is not much better. Farmers often find themselves waiting to certify their seed plots for long periods of time due to bureaucratic delay. There are very few government incentives or subsidies available for those looking to ramp up seed production. And it doesn't help either that private companies compete heavily in the seed trade. Small growers in Jammu are at a severe disadvantage as compared to these big private seed companies. There is some potential out there, and farmers actively want to engage in seed production, but it still has a lot of loose ends. Local seed production will continue to be a struggle as opposed to a success story for most people in the region, without supportive measures like training, infrastructure, and government backing delivered in a timely manner.

Seed Data & Government Reports: The Numbers Tell the Story

In Jammu, vegetable production is steadily increasing, according to the Indian Council of Agricultural Research (ICAR) and SKUAST-Jammu, but local seed production is still far behind the demand. Moreover, if you asked any progressive farmer today where they get their vegetable seeds from, the answer will most probably be from Punjab, Haryana, or even Maharashtra. And that is the biggest crack in the system. In Jammu and Kashmir, major vegetable crops cultivated include tomato, brinjal, chilli, cucumber, bottle gourd, and bitter gourd during the Kharif season, and cauliflower, cabbage, knol-khol, carrot, radish, peas, spinach, and fenugreek in the Rabi season. The region has a significant area dedicated to vegetable cultivation, with a production exceeding the national average. Vegetables are grown on a substantial area in Jammu & Kashmir, with a net area of 22,517.96 hectares and a gross area of 48,160.92 hectares. The region produces around 1539.59 thousand metric tons of vegetables.

According to SKUAST-Jammu, there is an estimated 450 to 500 tonnes of demand for vegetable seeds in the Jammu division every year. The scary part is that only a small amount is met by local certified seed production, while the majority comes from outside, often overpriced and unsuitable. Many of these seeds are hybrids, optimized for various agro-climatic zones, which can shift the results on our local farms. Adoption of certified or improved seeds by vegetable growers in Jammu & Kashmir remains extremely low, as indicated by a seed replacement ratio well below national recommendations. This suggests that the majority of farmers continue to rely on saved or uncertified seeds rather than locally available certified varieties.

This is a major issue, especially since districts such as Kathua, Udhampur, Samba and parts of Jammu have shown real potential under a small-scale seed production program. The government is not just sitting idly. Programs such as Rashtriya Krishi Vikas Yojana (RKVY) and Mission for Integrated Development of Horticulture (MIDH) are trying to stimulate better availability of seeds through subsidies, training and infrastructure development, but farmers have expressed a lot of disconnect between promise and reality. Reports indicate that procedural complexity and long timelines in application processing remain a significant barrier to farmer participation in various Jammu schemes.

In a positive twist to this story, Krishi Vigyan Kendras (KVKs) are slowly establishing themselves as the local stars in the tale. KVK Jammu is training numerous farmers in appropriate seed production, grading, and packaging. Farmers are seeing some promising signs- in some cases up to 30% increased income- after growing certified seed production of brinjal, capsicum, and bitter gourd. These numbers illustrate the fundamental point in this journey: when the proper knowledge and support reach the grassroots level, change starts to happen. So, even if the numbers seem overly technical, the take-home message is: Jammu has the land, Jammu has the climate, and Jammu has the farmers- we just need to connect the dots with the appropriate support. If we can achieve this, we could start to reverse the dependence on external markets and begin leading on local sources of the highest quality vegetable seeds.

Why Jammu is ready for seed revolution?

Walk through the fields of Jammu in early spring, and you'll see something remarkable- a quiet determination blooming along with the crops. From the fertile plains of R.S. Pura to the vegetable-rich belts of Kathua, Samba, and Udhampur, farmers aren't just growing food anymore- they're growing ambition. And that is precisely why Jammu is on the verge of a seed revolution. For years, this region has been treated like a consumer in the national seed market, buying what was already produced elsewhere, with farmers adapting to seeds inappropriate for the region's unique conditions. However, things are changing. Farmers are asking the question - if we can grow vegetables, why can't we also grow the seeds for next year's harvest? The demand for quality vegetable seeds is rising steadily, and Jammu's unique and diverse agri-climatic zones, from subtropical plains to sloping hilly zones, provide an ideal environment for seed production of many crops such as tomato, chilli, brinjal, cucumber, and okra. Furthermore, the new generation of educated, tech-savvy farmers in Jammu is more willing to adopt training, innovation, and collaboration.

Many of them are already working with SKUAST-Jammu, and Krishi Vigyan Kendras (KVKs) to learn the science that goes into seed purity, isolation techniques, and packaging things once beyond their reach. There is a visible shift from traditional to more organized, scientific practices. No longer is farming just farming; it's agri-preneurship. And the government schemes and institutions seem to be supportive, making this an even more promising trend.

Imagine the possibilities if Jammu had an even slight boost, such as improved access to breeder seeds, faster certification, marketing support, etc. Jammu could be a center for certified vegetable seed production, not just for the Union Territory of Jammu and Kashmir, but for neighbouring states as well. And most importantly- it isn't just seeds or money - it's self-reliance. When farmers produce their seed, they are no longer reliant on the unpredictable market or middlemen; they are in control of their fields, income, and ultimately their future. That is a true revolution - and Jammu is ready for it.

The Way Forward – Sowing the Seeds of a Brighter Future

Making Jammu a premier place for vegetable seed production will take not just good land and temperature, but vision, collaboration and dedication are also required. The potential is already deeply planted in the region's agriculture; however, it is time to capitalize on that capacity by establishing structured efforts to assist the farming community as a whole. A vital step is to encourage community-based seed-producing systems. The introduction of “Seed Villages” - groups of organized, trained farmers who collaboratively produce, maintain, quality seeds collectively, could be the difference for Jammu. Seed Villages can become living classrooms where new farmers learn from experienced ones, and all members care deeply. Workshops, field demonstrations and local dialect one-to-one mentorship experiences create a bridge to the knowledge gap. Local agronomists can provide education on rouging, maintaining proper isolation, seed harvesting practices, disease management practices, and handling post-harvest practices. All topics should be delivered practically so farmers can utilize items in their farming at home. Examples could be local State Agricultural Universities, SKUAST-Jammu, or Krishi Vigyan Kendra, to also step into this Emancipatory Education role in supporting farmer agri-entrepreneurship. The distance between knowledge is one thing, but people also need good infrastructure. Currently, many seed growers are struggling to find a dependable buyer or price for their seeds. By forming organized cooperatives or having a platform to sell directly, like a local marketplace or reputable seed companies, farmers can avoid the middleman price. One potential option could be local digital platforms, local agri-marts and showroom facilities where Jammu seed producers can engage wider markets, selling seeds at genuine prices for their certified seeds. There is also a great opportunity to involve women and youth. Seed production is significantly less stringent than conventional farming practices with respect to physicality and offers opportunities for entrepreneurship. There is also a tremendous opportunity to engage women and youth. Seed production is less physically intensive than conventional agriculture, allowing for entrepreneurship. Young agriculture graduates, rural youth, and women's self-help groups can all be trained and enabled to adopt seed production as a livelihood. This provides income and brings new energy and innovation into the sector. Finally, no transformation can take place without policy support. Government schemes must be made more accessible and actionable. Provide timely subsidy release, simplify the processes for certification, and offer better funding to launch seed units. Also, it is important to recognize farmers as seed entrepreneurs, to help farmers generate income, but to achieve the larger goal of providing food and nutritional security for the nation.

Jammu is poised for a monumental agricultural transition - from producing vegetables to becoming a chief provider of high-quality vegetable seeds. This move isn't just about the economic potential, but the innovation, the self-sufficiency and the added value put to our already high-value crops. With the right policies, infrastructure and training, Jammu can transition from its past identity to a vegetable seed capital of Northern India; a space that empowers farmers, connects markets, and influences natural advantages. The Region can plant the seeds for prosperity - not just for Northern India, but for the growing vegetable needs of our country.

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CLIMATE CHANGE AND ITS RIPPLE EFFECTS ON FLOWERING, FRUIT SET, AND YIELD: SAFEGUARDING THE FUTURE OF FRUIT CROPS

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Abstract

Climate change poses a significant threat to horticultural production worldwide, particularly affecting the flowering, fruit set, and yield of major fruit crops. Rising temperatures, altered rainfall patterns, increased frequency of extreme weather events, and elevated CO_2 levels are disrupting phenological stages of fruit crops, leading to reduced productivity and quality. This article examines the impact of climate change on key fruit crops, explores physiological and developmental challenges, and discusses adaptive strategies to mitigate adverse effects.

Key Words : Climate change, Fruit set, Yield, Adaptation strategies.

Introduction

Climate change is one of the most pressing challenges in agriculture today, with profound impacts on horticulture. Fruit crops, which are highly sensitive to temperature, water availability, and pollination dynamics, are particularly vulnerable. Flowering time, fruit set, and eventual yield are closely linked to climatic conditions. Variability in these factors not only reduces yield but also affects fruit quality, marketability, and farmer income.

Impact on Flowering

1. **Altered Flowering Time:** Climate change has led to noticeable shifts in flowering periods of fruit crops like apple, peach, and mango. Warmer winters and earlier springs can trigger premature flowering, which may not coincide with the peak activity of pollinators, reducing fruit set. In some cases, early blooms risk damage from unexpected late frosts, further affecting productivity and crop uniformity.
2. **Inadequate Chill Accumulation:** Temperate fruit crops such as apple, cherry, and plum require specific chilling hours to break dormancy and initiate uniform flowering. Rising winter temperatures due to climate change are reducing chilling accumulation, leading to irregular, delayed, or incomplete flowering. This directly results in poor fruit set, uneven fruit development, and reduced yields in affected regions.
3. **Flower Abortion:** Sudden heatwaves, temperature fluctuations, and erratic rainfall during flowering can induce significant stress in fruit crops, causing flower drop or abortion. High temperatures can impair pollen viability and stigma receptivity, while drought conditions can lead to hormonal imbalances that trigger flower loss. Crops like mango, citrus, and grapes are particularly vulnerable to such stresses, resulting in low fruit set.

Impact on Fruit Set

1. **Temperature Extremes:** High temperatures during flowering can lead to pollen sterility, reduced pollen viability, and poor fertilization, especially in sensitive crops like tomato,

citrus, and grapes. Heat stress can impair both male and female reproductive structures, significantly lowering fruit set and overall productivity.

2. **Water Stress:** Drought and irregular rainfall disrupt critical stages of pollination and fertilization by affecting flower development, pollen tube growth, and ovule viability. Water scarcity weakens plant health, leading to poor fruit set and reduced yield in crops such as mango, pomegranate, and citrus.
3. **Pollinator Decline:** Climate change-induced habitat loss, rising temperatures, and excessive pesticide use are causing a significant decline in pollinators like bees and butterflies. Since many fruit crops depend on insect pollination, reduced pollinator populations directly result in poor fruit set and lower harvests.

Impact on Yield and Quality

1. **Reduced Yield:** Extreme weather events such as droughts, floods, storms, and unseasonal temperature fluctuations cause substantial yield losses in fruit crops like mango, banana, and grape. These stresses disrupt growth, flowering, and fruit development, reducing both quantity and consistency of harvests.
2. **Fruit Quality Deterioration:** High temperatures and water stress negatively impact fruit size, colour, sugar accumulation, acidity, and shelf life, leading to inferior market quality. Fruits may become smaller, less flavourful, and more prone to post-harvest losses, reducing profitability for farmers.
3. **Pest and Disease Pressure:** Changing climate conditions are increasing the spread, survival, and reproduction rates of pests and diseases in fruit crops. Warmer temperatures and humidity shifts are enabling new pest invasions and disease outbreaks, causing additional yield losses and increasing reliance on chemical control.

Examples of Affected Crops

- **Apple:** Insufficient chilling and early blooming lead to reduced fruit set and quality.
- **Mango:** Irregular flowering, fruit drop, and increased pest incidence due to temperature fluctuations.
- **Grape:** Berry sunburn, reduced anthocyanin content, and lower wine quality due to high temperatures.
- **Citrus:** Flowering and fruit development adversely affected by heat and water stress.

Adaptation and Mitigation Strategies

1. **Breeding Climate-Resilient Varieties:** Developing fruit varieties that are tolerant to heat, drought, and reduced chilling requirements is essential for sustaining production under changing climates.
2. **Microclimate Management:** Implementing shade nets, windbreaks, and mulching helps regulate orchard microclimates, reducing heat stress and conserving soil moisture.
3. **Water Management:** Efficient irrigation techniques like drip systems and mulching help conserve water, improve plant health, and ensure stable yields during droughts.
4. **Pollinator Conservation:** Creating pollinator-friendly habitats and minimizing pesticide use support healthy pollinator populations, which are vital for successful fruit set.
5. **Agroforestry and Mixed Cropping:** Integrating trees and diverse crops within orchards enhances ecosystem resilience, reduces vulnerability to climate extremes, and improves soil and water management.

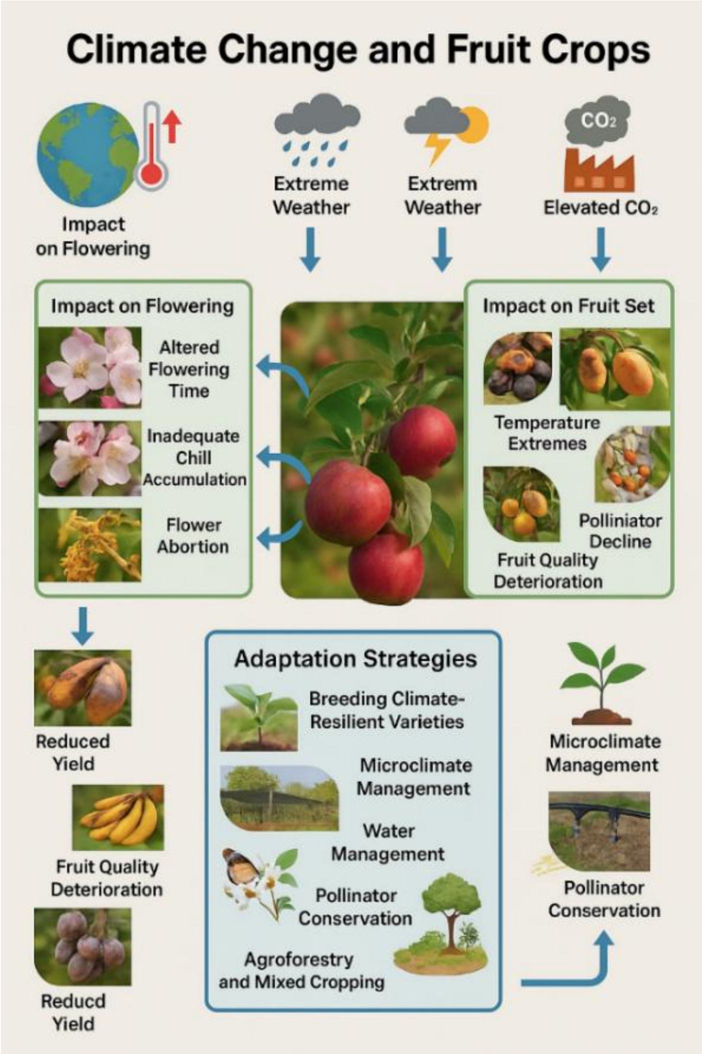

Figure 1: Climate change and Fruit Crops

Conclusion

Climate change is undeniably reshaping the landscape of fruit crop production, with significant impacts on flowering patterns, fruit set, yield, and overall quality. Rising temperatures, erratic rainfall, and increasing pest pressures are disrupting the delicate balance of horticultural systems, posing challenges to both productivity and farmer livelihoods. To safeguard the future of fruit cultivation, urgent action is required through the development and adoption of climate-resilient varieties, efficient water and microclimate management, pollinator conservation, and diversified farming systems. By integrating scientific innovations with traditional knowledge and ensuring supportive policies, horticulture can adapt to the changing climate while maintaining sustainability, profitability, and food security for future generations.

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ECOLOGICAL ROLE OF CORAL REEF

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Abstract
This covers the ecological benefits and services provided by coral reef ecosystems, which have main focus on their production. Reef mining and renewable resources are the two main categories of goods. We summarize what is currently known about the connections between biological communities of coral reefs around the world, functional groups of species, and ecological services. A foundation for handling uncertainty, upcoming changes, and ecological shocks is provided by management for increased resilience, which takes an account how human activity shapes ecosystem. The importance of coral reefs, their main dangers, and the need for conservation and management measures are all covered in this review article.

Keywords : Coral reef, Ecological services, Ecosystem based adaptation Coastal risk

Introduction

Coral reefs are known as "The Rain Forest of the Sea" because they support a vast tropical community. Although they only make up 1% of the earth's surface, coral reefs are stunning structures that serve as habitat for the vast majority of marine life. In tropical and subtropical environments, the majority of reef-building corals flourish. The calcium carbonate that makes up coral reef structure is linked to tiny zooxanthellae, which give coral polyps their vitality and stunning beauty. Corals were primarily found at depths of 100 meters, where sunlight is freely accessible and beneficial for photosynthetic zooxanthellae (Subha, 2013). Coral reefs are among the most productive and biologically diverse ecosystems on Earth (e.g. Odum and Odum, 1955; Connell, 1978). They provide a wide range of products and services to large populations, including seafood, recreational opportunities, coastal protection, and cultural and aesthetic advantages (e.g. Smith, 1978; Ku Èhlmann, 1988; Spurgeon, 1992; Done *et al*., 1996; Peterson and Lubchenco, 1997).

Indian coral reefs diversity

Four regions of India that includes Gulf of Mannar (Tamil Nadu), the Andaman and Nicobar Islands, the Lakshadweep Islands, and the Gulf of Kachchh (Gujarat) had the majority of coral. Along the banks of Kerala, Maharashtra, and a portion of the east coast, there have also been reports of coral patches. Up to 25% of the total fish caught in the area is provided by them (Rajasuriya *et al*., 2002).

1. Ecological goods and services of coral reefs

Fringing reefs, barrier reefs, atolls, and platform reefs are the four primary forms of coral reefs. In addition to being sinks for pollutants and organic and inorganic debris, mangroves and seagrass beds can create a habitat with clear, nutrient-poor water that encourages the formation of coral reefs offshore (e.g. Kuhlmann, 1988; Ogden, 1988), but see also Szmant (1997) **but** exploring the possibility that reefs could be able to use and profit from larger nutrient fluxes than current paradigms suggest. Seagrass beds and mangroves can grow in an environment that is conducive to geologic time because coral reefs act as physical barriers against ocean waves and currents.

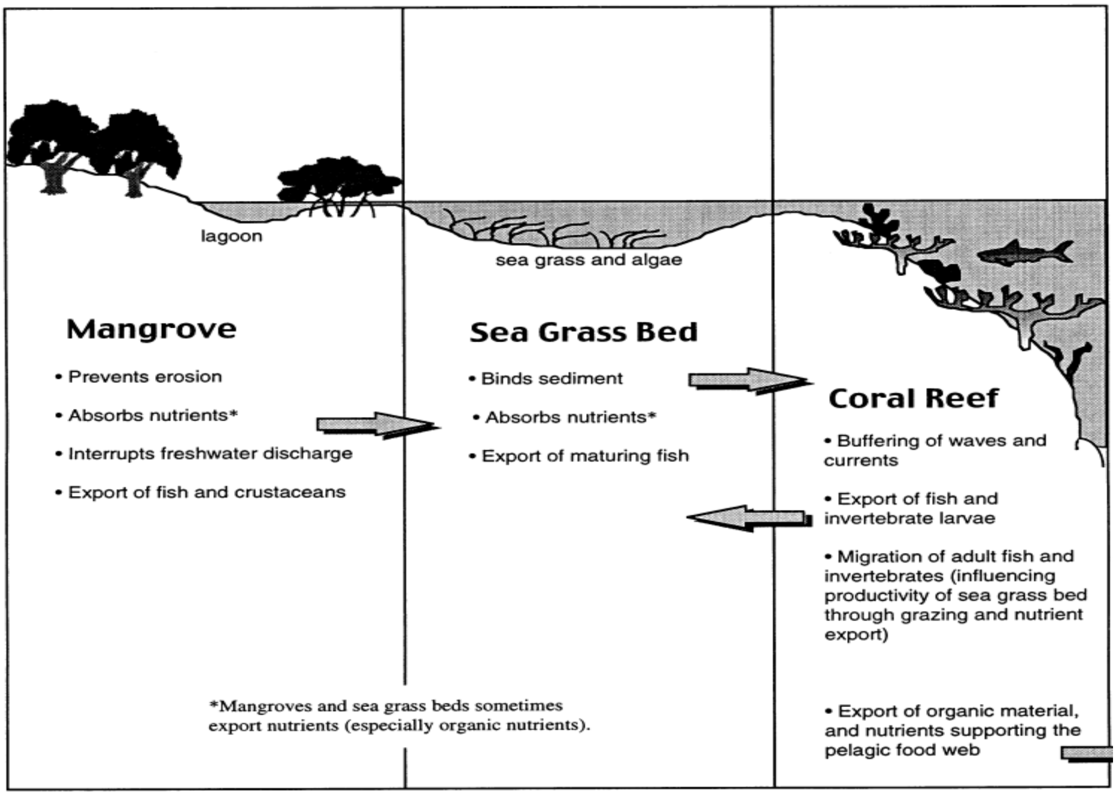

Fig. Interactions in the tropical seascape, showing the connections between mangroves, sea-grass beds and coral reef. (**Source**: Adopted from white (1986) and Ogden (1988).

2. Ecological good

a) Renewable resources

Numerous seafood products, including fish, mussels, crustaceans, sea cucumbers, and seaweeds, are produced by reefs (e.g. Craik et al., 1990; Birkeland, 1997a). Reef-related fisheries constitute approximately 9–12% of the world's total fisheries (Smith, 1978) and in some parts of the Indo Pacific region, the reef fishery constitutes up to 25% of the total fish catch (Cesar, 1996). Numerous seafood products, including fish, mussels, crustaceans, sea cucumbers, and seaweeds, are produced by reefs (e.g. Sorokin, 1993; Carte´, 1996; Birkeland, 1997a). Many species of seaweed are collected from reefs to be used in the production of agar and carrageenan (Birkeland, 1997a) and as manure (Craik *et al.,* 1990), and coral skeletons have proven to be promising in bone graft operations (Spurgeon, 1992). Not only are mother-of-pearl shells (Trochus spp.) and gigantic clams (Tridacna spp.) harvested for food, but they are also sold as souvenirs and jewellery. Corallium rubrum, or red coral, is another example of a decorative item that sold for US$900 per kilogram in 1980. (Goh and Chou, 1994).

b) Mining of reefs

Using hard corals for construction and to make cement, mortar, and lime are two examples of the use of coral reefs that is clearly harmful (Dulvy et al., 1995). In agriculture, lime is also utilized as a pH regulator (Cesar 1996), and in some areas, coral debris is also collected and crushed for use as fertilizer, and lime is also utilized in agriculture as a pH regulator (Kuhlmann, 1988). Reef organism biomass is transformed into mineral oils and gas by physicochemical processes that take place over millions of years. The porous limestone of ancient reef structures in Siberia, Saudi Arabia, the United States, and Canada may contain oil. (Sorokin, 1993; Hodgson, 1997). An increasing amount of research on mineral oils is being funded by the petroleum sector. (Kuhlmann, 1988), and Oil reserves in old reef structures can be found with the aid of studies of the ecology and geomorphology of contemporary reefs (Sorokin, 1993).

3) Ecological services

a) Physical structure services

Without coral reefs protecting the shoreline from currents, waves, and storms there will be loss of land due to erosion. In Indonesia, Cesar (1996) estimated that between US$ 820–1 000 000 per km of coastline was lost due to decreased coastal protection as a consequence of coral destruction. The capacity of coral reefs to dissipate wave energy creates lagoons and sedimentary environments. Coral reefs thus physically create favourable conditions for the growth of sea-grasses and mangrove ecosystems (Birkeland, 1985; Ogden, 1988). Coral reefs generate the fine coral sand supplying shores with the white sand characteristic of tropical islands and one of the main attractions in beach tourism (e.g. Richmond, 1993). Bioeroders, such as algae, sponges, polychaetes, crustaceans, sea urchins, and fishes are important in producing the reef sediments (rubble, sand, silt, and clay) (Trudgill, 1983).

b) Biotic services within the ecosystems

Coral reefs, one of the world's most species-rich environments, are crucial to conserving a massive genetic library and biological variety for coming generations. These species include keystone process species, which control ecosystem functions and processes, such as through predation and grazing. (Hughes, 1994; McClanahan *et al*., 1994; Done *et al*., 1996). In most reefs there are many species within each functional group (cf. Choat and Bellwood, 1991; Roberts, 1995). Many of those species do not appear to perform key functions but may be able to take over such functions (Peterson and Lubchenco, 1997) if the keystone process species within a functional group is lost (McClanahan *et al*., in press). Herbivorous fishes and sea urchins from the reefs move to sea-grasses for grazing and influence plant community structure there (e.g. Birkeland, 1985), and may serve as a food source for predators in other systems, as well as food for humans (Parrish, 1989; Spurgeon, 1992). the pelagic juvenile stages of many reef organisms that drift into these adjacent ecosystems serve as a food source for commercially important fishes, or they may settle and mature until harvested by fishermen (Spurgeon, 1992).

c) Social or cultural services

Recreation is enhanced by coral reefs. Reefs have great recreational value, as demonstrated by the vast amount of money generated by tourism. (Dixon *et al*., 1993; Pendleton, 1995; Cesar, 1996). Coral reefs are beautiful places. (cf. de Groot, 1992). There is no denying the monetary worth of all the novels, movies, and artwork that draw inspiration from coral reefs. Numerous local communities rely on coral reefs for their livelihoods. For instance, it's estimated that pollution and overfishing have destroyed Philippine reefs, costing at least 100,000 fisherman their employment. (McAllister, 1988). In this way, reefs provide another significant and sometimes overlooked function: they stabilize the institutional and social frameworks that support cooperative fishing in more established coastal communities. (Birkeland, 1997a).

4) Economic valuations of coral reef ecological goods and services

Better management and protection may result from the economic importance of coral reefs, their products, and their services. The economic benefits of tourism and fishing have been the main focus of reef valuation research. (Hodgson and Dixon, 1988; Dixon et al., 1993; Barton, 1994; Driml, 1994; Cesar, 1996). People don't often realize how dependent they are on ecosystem support, ecological services, and essential goods. We have maintained that a large number of ecological goods and services that are rare and contribute to well-being satisfy the requirements for economic value, but for which people do not yet have preferences (Costanza and Folke, 1997).

Coral importance to human beings

Corals are mostly used to monitor environmental and climatic conditions. In agriculture, lime is also utilized as a pH regulator (Cesar 1996 Radioactive carbon dating is used to determine changes in sea levels and physical characteristics of water quality using fossilized corals. Coral chemicals have been found to have significant medical applications, including the treatment of cancer, AIDS, pain, and other abnormalities, as well as a variety of bone operations. Due to their vibrant nature, corals are highly sought-after for high-end jewellery and ornaments. Corals are also a good supply of lime and calcium carbonate, which are needed as raw materials for a variety of construction projects.

The concept of coral culture emerged as the need for corals grew, with researchers, scientists, decorative dealers, and businesspeople primarily cultivating corals for their trade and to satisfy their passion for aquariums (Subha, 2013) and helpful to minimize the coral degradation. The people who live along the coast in many other coastal nations benefit economically from tourism activities like scuba diving and snorkeling. Coastal boundaries are shielded from storms and waves by coral reefs, which also serve as breeding grounds and nurseries for a variety of aquatic species, including fish and shellfish (Cabral and Geronimo, 2018).

Human impacts and loss of resilience done

In this regard, many of the reefs' resources are also the reason for their demise because many of their uses are unsustainable (Weber, 1993). Destructive fishing techniques including cyanide or dynamite fishing, fishing with small seine nets, collecting reef species for the curio trade, mining coral for lime, unregulated tourism, and oil extraction are all included in the list of destructive activities. (e.g. Hawkins and Roberts, 1994; Johannes and Riepen, 1995; Dulvy *et al*., 1995).

According to several studies, human influence in Southeast Asia has put approximately 60% of the coral population at risk and 80% of the population in the endangered category (Wilkinson, 2008). According to study forecasts, around 90% of the world's coral reefs may be lost by 2030 if the ratio of climate change to human influence remains constant, and they will fall into the extinct category by 2050 (Kleypaset *al*., 2006; Burkeet *al*., 2011). But it seems that long-term, persistent human-caused disturbances (such nutrient releases and overfishing) are more harmful to coral reefs (e.g. Richmond, 1993; Hughes, 1994; Connell *et al*., 1997).

Bleaching

The delicate balance between reef corals and their symbiotic microalgae (zooxanthellae) is being disrupted by a number of natural and man-made factors. Because corals lose colour as a result of this, the zooxanthellae (or their pigment) frequently disappear, a process known as bleaching (e.g. Brown, 1987; Goreau and Hayes, 1994). This extensive bleaching is likely the result of high-water temperature that are associated with one of the most powerful El Ninos this century (ISRS, 1998). Moreover, a number of additional stressors can cause bleaching, such as reduced salinity brought on by increased runoff from urbanization and clear-cutting (Moberg *et al.*, 1997), discharge of harmful materials, including heavy metals (Harland and Brown, 1989), and high UV radiation (Goreau and Hayes, 1994).

Fig., A healthy coral (left) and a coral that has experienced bleaching (right).
(**Source**: Photo credit: Henry Wolcott/Marine Photobank)

Human-induced increases in CO2 in the atmosphere pose a threat to reef calcification as well because they lower carbonate concentrations in the water, which in turn inhibits reef coral development (Brown, 1997; Pennisi, 1997).

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CRISPR AND CROPS: EDITING THE FUTURE OF FOOD SECURITY

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Introduction

Feeding the world has never been more challenging. By 2050, the global population is projected to reach **9.7 billion**, demanding at least **50% more food production** than today. This has to be achieved with shrinking farmland, scarce water, and under the looming threat of climate change. Traditional plant breeding helped humanity achieve the **Green Revolution,** doubling cereal yields in countries like India. Genetic modification (GMOs) introduced new traits, from Bt cotton to Golden Rice. But these approaches face limitations—breeding is slow, and transgenic GMOs face regulatory hurdles and consumer skepticism. This is where **CRISPR- Cas gene editing** has emerged as a **game-changer.** Often called “molecular scissors,” CRISPR can precisely edit a plant’s DNA—turning genes on or off, or making targeted changes—to improve resilience, nutrition, and productivity. Unlike older genetic engineering, CRISPR edits are fast, accurate, and often indistinguishable from natural mutations, making them more widely accepted. In a world threatened by food insecurity, CRISPR is not just a scientific breakthrough and it could be a lifeline.

Importance of CRISPR for Agriculture

Agriculture has always relied on plant improvement. Farmers traditionally selected and saved seeds, breeders later accelerated this with hybridization, and biotechnology introduced transgenes. But CRISPR takes plant improvement to a new level:

- **Precision:** Unlike random mutations or broad chemical mutagens, CRISPR can target a single gene.
- **Speed:** Traits that once took 10–15 years to develop can now be introduced in 2–4 years.
- **Cost-effectiveness:** Gene editing is less expensive than traditional GMOs.
- **Acceptability:** Because many CRISPR edits do not involve adding foreign DNA, regulators and consumers view them differently from GM crops.

This combination makes CRISPR uniquely powerful for tackling global food challenges—**disease outbreaks, climate shocks, post-harvest losses, and malnutrition.**

Core Applications of CRISPR in Crops

1. Disease Resistance

Plant diseases can wipe out 20–40% of global crop yields annually. CRISPR offers precise tools to fight them:

- **Wheat resistant to powdery mildew:** Scientists edited the MLO gene, making plants immune without pesticides.
- **Cassava resistant to mosaic virus:** A breakthrough for food security in Africa, where cassava is a staple.
- **Rice resistant to bacterial blight:** By tweaking susceptibility genes, researchers created varieties that resist one of Asia's deadliest rice diseases.

In India, ICAR scientists at IARI are using CRISPR to develop **blast-resistant rice**, a disease that affects millions of farmers.

2. Climate Resilience

As temperatures rise and rainfall becomes erratic, crops need to adapt fast. CRISPR is helping create climate-smart varieties:

- **Drought-tolerant maize** with enhanced root structures.
- **Heat-resistant tomatoes** that continue flowering even at 40°C.
- **Salt-tolerant rice and soybean** for coastal areas affected by sea-level rise.

These innovations are critical for India, where **60% of agriculture is rainfed** and climate extremes are already reducing farm incomes by 15–20%.

3. Nutritional Improvement (Biofortification)

Hidden hunger—deficiency of micronutrients like iron, zinc, and vitamin A—affects nearly **2 billion people** worldwide.

CRISPR enables crops to be **biofortified naturally**

- **High-iron and high-zinc rice** developed for South Asia.
- **Wheat with reduced gluten**, offering safer food for those with celiac disease.
- **Healthier edible oils** from mustard and soybean with better fatty acid profiles.

For India, where anemia and malnutrition remain widespread, CRISPR-based nutrition enhancement could directly improve public health.

4. Reducing Food Waste

Globally, about **30% of food is lost or wasted** before it reaches consumers. CRISPR can reduce this by extending shelf life:

- **CRISPR-edited tomatoes** with delayed ripening for longer storage.
- **Non-browning mushrooms**, reducing rejection during marketing.
- **Bananas with slower ripening genes turned off**, cutting post-harvest losses.

This is especially relevant for India's fruits and vegetables, where 40% is lost due to poor storage and transportation.

India's Role and ICAR Initiatives

India is cautiously but actively exploring CRISPR in agriculture. Key developments include:

- **Policy Change:** In 2022, the Government of India exempted certain gene-edited crops (those without foreign DNA) from the strict GMO regulations, clearing the path for faster approvals.

- **Research:**
  - **ICAR-IARI, New Delhi:** Working on CRISPR-based rice and wheat for disease resistance.
  - **NIPGR, New Delhi:** Researching oilseed crops with improved fatty acid profiles.
  - **National Agri-Food Biotechnology Institute (NABI), Mohali:** Developing nutrient-rich fruits and vegetables.
- **Collaboration:** India is partnering with CGIAR and international universities to accelerate gene-editing innovations for crops like sorghum, pearl millet, and pulses.

Global Success Stories

- **United States:** CRISPR-edited soybeans with healthier oil profiles are already on the market.
- **Japan:** Approved CRISPR-edited tomatoes with high GABA content, beneficial for reducing blood pressure.
- **China:** Pioneering CRISPR-edited rice and wheat lines resistant to major diseases.
- **Africa:** Trials of virus-resistant cassava and maize are showing promising results.

These stories demonstrate that CRISPR is moving from the lab to the field, proving its practical value.

Benefits Beyond Yield

CRISPR goes beyond boosting productivity. It can:

- Reduce pesticide use, lowering farmer costs and chemical residues.
- Enhance resilience, ensuring stable harvests during climate shocks.
- Improve nutrition, contributing to public health.
- Reduce food waste and improve supply chains.

For smallholder farmers, especially in countries like India, CRISPR could mean **higher incomes, better food, and more security against uncertainty.**

Challenges

Despite its promise, CRISPR faces challenges:

- **Regulatory clarity:** Not all countries treat gene-edited crops the same way.
- **Ethical debates:** Should humans "edit" nature? How far should we go?
- **Equity concerns:** Will small farmers have access, or will big companies dominate?
- **Consumer acceptance:** Public understanding of CRISPR remains low.

Conclusion

CRISPR is more than a scientific tool it is a hope for feeding the future. As climate change threatens harvests and malnutrition persists, CRISPR offers solutions that are precise, sustainable, and farmer-friendly. The future of farming may not lie in more fertilizers or more land, but in smarter crops designed at the genetic level.

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DISPERSAL OF SOIL MICROBES AND ITS SIGNIFICANCE IN ECOSYSTEMS

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Abstract
This article explores the mechanisms and significance of soil microbial dispersal, emphasizing its vital role in ecosystem functionality, nutrient cycling and soil health. Microbial dispersal occurs through physical pathways such as water movement and soil cracks, biological vectors like soil fauna and plant roots and atmospheric transport via wind and dust. Dispersal mechanisms are categorized into active which is driven by microbial motility, growth and where in case of passive facilitated by external forces such as water, wind and human activities. Factors influencing dispersal include soil texture, moisture, plant cover and land disturbance. Microbial movement impacts community composition, ecological resilience and agricultural productivity, with benefits including enhanced plant-microbe interactions and pathogen suppression. Understanding these processes informs strategies for sustainable soil management, habitat restoration and crop health. Microbial dispersal's complex interplay of physical, biological and environmental factors underscores its importance in maintaining soil ecosystem stability and resilience for future ecological and agricultural advancements.

Keywords: Microbial dispersal, active dispersal, passive dispersal, dispersal mechanism and plant growth

Introduction

Soil microbes are integral to ecosystem functioning, influencing nutrient cycling, plant health and soil structure. The dispersal of these microorganisms across spatial scales is a fundamental process that determines microbial community composition and ecological dynamics in terrestrial environments. Understanding how soil microbes disperse, the factors affecting their movement and the ecological implications provides insights into soil health, agriculture and environmental resilience.

Mechanisms of Microbial Dispersal

Microbial dispersal in soil occurs via various mechanisms, primarily physical, biological and atmospheric pathways. Physical dispersal includes movement through soil pores, water films and soil cracks. Microbes can be transported by soil water movement, such as rainwater percolation or irrigation, which acts as a vector for microbial transport (Santini *et al*., 2018). Biological dispersal relies on vectors like soil organisms such as arthropods, earthworms and insects that aid microbial movement by their activities, including burrowing or consuming and excreting microbes (Torsvik and Ovreas, 2002). Additionally, microbes can be dispersed through attachment to plant roots or organic matter, which can be transported by biotic activities.

Atmospheric dispersal, especially for microbes capable of forming spores or resisting desiccation, allows for long-distance movement via wind or dust particles. This form of dispersal can introduce novel microbial taxa into soil communities, promoting diversity (Bowers *et al*., 2011). The ability of microbes to survive and remain viable during aerial transport significantly influences their dispersal success.

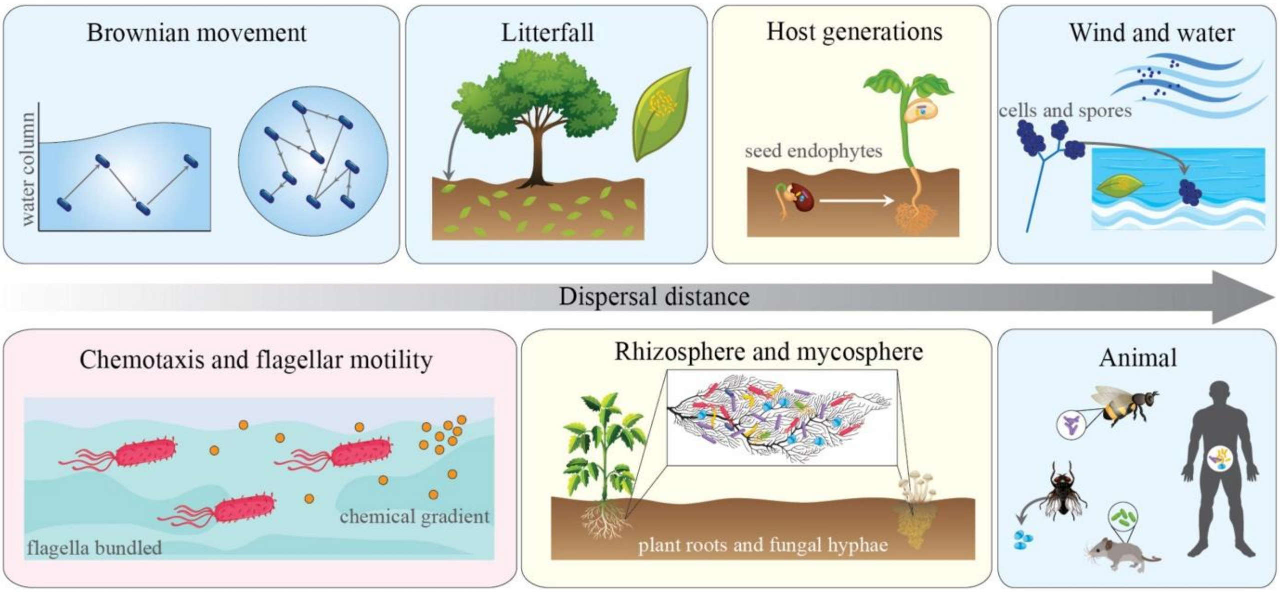


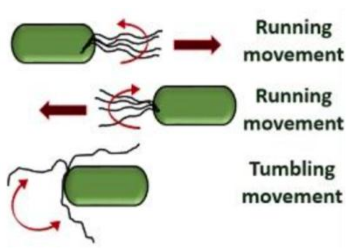
Fig. 1: Types and Mechanism of Microbial dispersion
(Custer *et al*., 2022)

Active and Passive Dispersal of Soil Microbes

Microbes distribution within soil environments is governed by various dispersal mechanisms, broadly classified into active and passive dispersal. Understanding both active and passive dispersal mechanisms where active dispersal involves microbial movement driven by motility or biological activity and passive dispersal relies on external forces like water, wind, fauna, or human activities is crucial for managing soil ecosystems effectively. Active dispersal supports local adaptation and rapid responses to environmental changes, while passive dispersal facilitates gene exchange, colonization of new niches and large-scale microbial distribution across landscapes.

1. Active Dispersal of Soil Microbes

Active dispersal refers to the movement of microbes driven by their own motility or biological activity. Active dispersal is generally limited too short to moderate distances, constrained by soil pore size, moisture and nutrient availability. It plays a crucial role in maintaining microbial diversity and enabling rapid responses to environmental changes. Many soil microbes possess specialized structures or mechanisms enabling them to navigate their environment:



- **Motility Structures:** Many soil microbes utilize flagella-based motility to navigate their environment. Bacteria such as *Pseudomonas* and *Bacillus* species possess flagella that enable active swimming through water films within soil pores. This motility facilitates movement toward favourable conditions, such as nutrient sources or optimal oxygen levels, through chemotaxis. By actively relocating, these bacteria enhance their survival, colonization and interactions within complex soil ecosystems. Their ability to move efficiently in microhabitats is crucial for establishing and maintaining populations in diverse soil niches (Suna *et al*., 2018).

- **Biofilm Formation:** Certain microbes form structured biofilms on soil surfaces, creating complex communities embedded in a self-produced extracellular matrix. These biofilms enable microbes to adhere to surfaces, protect against environmental stresses and facilitate resource sharing. Within soil, biofilms support localized movement and enhance microbial persistence, allowing bacteria and fungi to colonize specific niches effectively. The formation of biofilms also promotes the exchange of nutrients and genetic material, aiding in adaptation and survival. Such communities are vital for soil health, influencing nutrient cycling and microbial dynamics (Ghannoum *et al*., 2020; Flemming & Wingender, 2010).

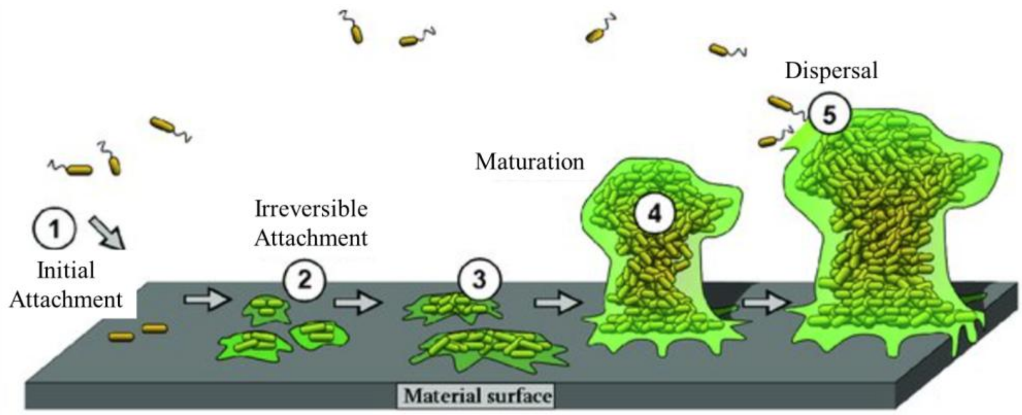


Fig. 2: Bacterial adhesion and biofilm formation
(Moriarty *et al*., 2011)

- **Growth and Reproduction:** Microbial growth and reproduction contribute significantly to dispersal within soil environments. As populations expand locally, some cells can detach and colonize new microsites, facilitating spatial spread. Reproductive processes, such as cell division, increase microbial biomass, which can then be transported via water movement, soil particles, or biotic vectors. This proliferation-driven dispersal helps microbes adapt to changing soil conditions and access new resources, maintaining ecological stability. The capacity for local growth and subsequent dispersal is fundamental for microbial colonization and resilience in heterogeneous soil matrices (Custer *et al*., 2022).

2. Passive Dispersal of Soil Microbes

Passive dispersal involves the movement of microbes via external forces or vectors, without their own motility. This process often governs long-distance distribution and colonization of new habitats. Passive dispersal mechanisms are typically responsible for the broad-scale distribution and colonization of microbes, often introducing rare or novel taxa into soil communities:

- **Water Movement:** from rainfall, irrigation and surface runoff transports microbes via soil water films and percolating water, enabling their dispersal across various soil zones. This process helps distribute bacteria and fungi, promoting microbial colonization in different microhabitats within the soil (Santini *et al*., 2018).
- **Airborne Transport:** Many microbes produce spores or resistant cell forms that can become aerosolized and dispersed by wind. Dust particles and aerosols carry these microbes over long distances, allowing them to colonize new environments. This airborne transport contributes

to microbial diversity, dispersal and the spread of different taxa across soil and other habitats (Bowers *et al*., 2011).

- **Biotic Vectors:** Soil fauna such as insects, earthworms and plant roots serve as vectors for microbial dispersal. For instance, earthworms can ingest microbes from the soil and deposit them elsewhere through castings, while plant roots can extend microbial communities to new sites via rhizosphere expansion.
- **Human Activities:** Agricultural practices, soil transportation and land disturbance often lead to passive dispersal, either intentionally (e.g., soil amendments) or unintentionally (e.g., machinery movement).

Factors Influencing Microbial Dispersal

Several environmental and biological factors influence the dispersal of soil microbes:

- **Soil Structure and Texture:** Fine soils with small pores restrict microbial movement, while coarse soils with larger pores enhance dispersal, allowing microbes to spread more easily through the soil matrix (Negi *et al*., 2025).
- **Moisture Content:** Water availability is essential; saturated soils facilitate water-based microbial transport, whereas dry conditions limit movement, affecting microbial distribution and activity within the soil environment.
- **Plant Cover and Root Activity:** Plant roots act as pathways for microbes, with rhizosphere extension and root exudates attracting and supporting microbial communities, promoting their dispersal and colonization in the soil (Estendorfer, 2023).
- **Disturbance and Land Use:** Activities like tillage, agriculture and development can disrupt existing microbial communities or open new dispersal routes, influencing microbial diversity and spatial distribution.

Ecological and Agricultural Significance

Dispersal plays a critical role in shaping microbial diversity, community assembly and functional potential within soils, influencing ecological resilience and ecosystem functioning. It is essential for recolonization following disturbances such as erosion or contamination, thereby maintaining soil health and supporting plant-microbe interactions that are vital for plant growth and productivity. The dispersal of beneficial microbes, including mycorrhizal fungi and nitrogen-fixing bacteria, can enhance plant development, whereas the spread of pathogenic microbes poses risks to crops and natural vegetation. Insights into these processes enable the development of strategies such as microbial inoculation and habitat restoration, which leverage natural dispersal mechanisms to improve soil health, control pathogens and promote helpful microbial interactions that strengthen sustainable agriculture and ecosystem resilience.

Conclusion

Soil microbial dispersal involves a complex interaction of physical, biological and environmental factors that shape community structure and influence ecosystem functions, with significant implications for agriculture and environmental management. Dispersal occurs through both active and passive mechanisms: active dispersal, driven by microbial motility and biological activity, supports localized movement and community stability, while passive dispersal, facilitated by water, wind, animals and human activities, allows microbes to travel greater distances and colonize new areas. Understanding these processes', including dispersal distances and survival during transit, is vital for advancing soil microbial ecology. Harnessing these mechanisms can improve sustainable soil management and ecological restoration, ensuring healthy microbial communities that promote plant growth, suppress pathogens and maintain ecosystem resilience. Future research in this area will deepen our knowledge of microbial dispersal dynamics in soils.

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EDIBLE INSECTS: SUSTAINABLE PROTEIN SOURCE OR FUTURE PEST? THE INDIAN CONTEXT

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Abstract

In the bustling markets of Northeast India, vendors display plates of fried crickets and roasted beetle larvae alongside traditional vegetables, a sight that might surprise many Indians but represents centuries of culinary tradition. As India grapples with feeding its growing population of 1.4 billion people while facing mounting environmental challenges, the question of whether edible insects represent a sustainable protein solution or merely another complication has gained unprecedented urgency.

The Scale of India's Protein Challenge

Despite being the world's greatest producer of pulses, accounting for 25% of worldwide output, India faces a paradoxical protein shortage. More than 70% of Indians are protein deficient, according to recent studies, ingesting only 0.6 grams of protein per kilogram of body weight, as opposed to the recommended 0.8–1 gram. The situation is considerably worse in rural regions, where despite the ample availability of foods high in protein, over two-thirds of households in India's semi-arid tropics consume less protein than is advised (Manna *et al.*, 2022).

According to the Food Safety and Standards Authority of India, 39% of people do not eat a diet that is nutrient-adequate, and 74% of people cannot afford a healthy diet. India's hunt for alternative protein sources has become a national need in light of the Global Report on Food Crises 2025, which warns that 295 million people worldwide are experiencing rising levels of food insecurity (FSIN, 2025).

India's Rich Entomophagy Heritage

In India, eating insects has a long history that dates back to the Vedic era, unlike what the general public believes. According to research, between 250 and 300 different species of edible insects are consumed by Indian populations; tribal areas are where this practice is most common. With Nagaland alone ingesting 92 distinct species (Mozhui *et al.*, 2017), Manipur following with 69, and several more states adding to a diverse tapestry of entomophagy practices, the northeastern states are at the forefront of this tradition (Thangjam *et al.*, 2020).

Regional Distribution and Species Diversity

There are notable regional differences in the diversity of edible insects in India (Chakravorty, 2014; Haldhar *et al.*, 2021). The Nyishi and Galo tribes of Arunachal Pradesh in Northeast India eat at least 81 species from 26 families in five orders, with the largest group being the Coleoptera (beetles) with 24 species. More than 500 species of edible insects from Northeast India, such as grasshoppers, caterpillars, beetles, termites, bees, wasps, ants, and cicadas, have been identified by ATREE experts in recent studies.

The most commonly consumed insects across India include:

- **Coleoptera (beetles)**: 34% of total consumption, including palm weevils and wood borer larvae

- **Orthoptera (grasshoppers and crickets)**: 24% of consumption
- **Hemiptera (true bugs)**: 17%, including various stink bugs and plant feeders
- **Hymenoptera (bees, wasps, ants)**: 10%, particularly red ant eggs and honey bee larvae
- **Odonata (dragonflies)**: 8%, especially popular among certain tribal communities

Traditional Preparation Methods

Although preparation techniques differ by species and region, they usually include boiling, smoking, frying, or roasting. While winged termites are cleaned, roasted, and consumed in Odisha, red tree ants are cooked with spices in Assam. Insect larvae gathered from date palms and leafy trees are especially popular among the Muria tribe in the Bastar area of Madhya Pradesh. Some cultures ground insects into powder and dry them for subsequent use in meat and vegetable curries (Defoliart, 2002).

Nutritional Powerhouse and Therapeutic Benefits

Edible insects eaten in India have remarkable nutritional profiles, according to scientific studies. In addition to beneficial polyunsaturated fatty acids, dietary fiber, vitamins and minerals like iron, magnesium, zinc, calcium, copper and manganese, these insects offer high-quality protein with essential amino acids that are comparable to those found in traditional meat sources (Devi *et al.*, 2024).

Traditional Medicine Applications

In addition to using insects for food, many Indian groups also use entomotherapy, or the use of insects for therapeutic purposes. Nine entomophagy species with therapeutic qualities were found in studies describing the ethnotherapeutic practices of the Tangkhul, Mao and Poumai populations in Manipur. These species were utilized to cure a variety of illnesses, such as sore throats, mouth ulcers, jaundice, bodily aches and wound healing. These insects, which represent priceless indigenous knowledge systems, are used by traditional healers in treatments that have been handed down through the generations (Malakar, 2022).

The Modern Indian Insect Industry

Due to growing awareness of sustainability and protein substitutes, India's commercial insect farming industry is expanding significantly. The country is well-positioned for the growth of insect farming due to its tropical environment, plentiful food waste, and established agricultural infrastructure.

Leading Companies and Investment

Loopworm, which is now running at 10% capacity, estimates that, when fully operational, it may generate $15 million in income annually. Investors Omnivore and WaterBridge Ventures contributed $3.4 million in seed finance to India's first insect farming firm in 2022. The company, which mainly targets the aquaculture and pet food markets, runs a plant in Bangalore that can produce 6,000 tons of silkworm and black army fly protein yearly (Ngige, 2023).

GreenGrahi recently secured ₹32 crore ($3.8 million) in a record-breaking seed funding round led by Avaana Capital, marking the largest investment in India's insect-based protein space. The business turns agricultural waste into biological agricultural inputs, useful oils, and high-performance insect proteins using Black Soldier Fly larvae. GreenGrahi's products show remarkable results, including a 7% rise in shrimp survival rates, a 10% increase in weight growth and a 28% increase in poultry egg output, and a 25–30% increase in agricultural yields (Watson, 2024).

Market Focus and Applications

Indian insect farming businesses mostly focus on animal feed uses, in contrast to worldwide trends that emphasize human consumption. While meeting urgent demands in the pet food, poultry, and aquaculture sectors, this strategy focus is in line with current cultural preferences (Huis and Rumpold, 2023). The strategy makes use of India's status as a significant producer of aquaculture, where costly imported fishmeal and soy-based feeds can be substituted with insect meal.

Regulatory Landscape and Challenges

The laws governing edible insects in India are still complicated and constantly changing. Through the Food Safety and Standards Act of 2006, the Food Safety and Standards Authority of India (FSSAI) regulates all food items; nevertheless, insects as food additives are subject to a gray area of regulations. In the absence of specific clauses, meals derived from insects are governed by Novel Food Regulations that demand prior authorization from food authorities (FSSAI, 2010).

Safety Concerns and Standards

There are valid safety concerns that contribute to the regulatory uncertainty. Microbial contamination, pesticide residues, heavy metal bioaccumulation, and allergic reactions are possible hazards, especially for those who are allergic to crustaceans because of allergy cross-reactivity. While microbial concerns may be managed with proper hygiene, chemical pollution presents more serious difficulties, according to Dr. Satyanarayana KV of Sathguru Management Consultants.

Insects as food ingredients are not the main focus of current FSSAI rules, which are more concerned with pest control in food processing and storage facilities (FSSAI, 2018). There is a regulatory gap with new insect food applications because the authority upholds stringent regulations for avoiding insect contamination in conventional food items.

Cultural Barriers and Consumer Acceptance

Edible insects are still not widely accepted by Indian consumers, despite customs in some areas. According to research, acceptance patterns are greatly influenced by psychological variables, religious beliefs and cultural obstacles. The practice has little traction in urban marketplaces and is mostly restricted to tribal populations in Northeast India and few rural areas (Singh, 2022).

Social and Economic Factors

According to consumer acceptability surveys, views on the eating of insects can be positively influenced by convenience, perceived health benefits, and environmental consciousness. However, logical thoughts regarding nutrition and sustainability are frequently overshadowed by cultural taboos and social conventions (Siddiqui *et al.*, 2023). Perceptions may progressively change as a result of the younger generation's increased environmental knowledge, but major obstacles still exist (Alhujaili *et al.*, 2023).

Since many customers equate eating insects with poverty rather than making a sustainable option, economic considerations are also very important. These misconceptions might be dispelled with the aid of marketing campaigns and educational programs that highlight the advantages of nutrition and the environment.

Environmental Benefits and Sustainability

Comparing insect farming to traditional animal production reveals significant environmental benefits. The method produces very little greenhouse gas emissions and drastically reduces the amount of land, water, and feed resources needed. Sustainable insect farming operations are made possible by India's tropical environment and plentiful agricultural waste streams.

Resource Efficiency

According to research, insect farming may be carried out in controlled conditions that are appropriate for urban areas and utilizes a lot less water than conventional animal production. The capacity to transform organic waste into high-quality protein simultaneously tackles the problems of waste management and protein production.

The most widely cultivated species in India, black soldier fly larvae, are capable of processing a variety of organic waste streams, such as food waste, agricultural leftovers and byproducts of food processing. Because of these capabilities, insect farming can produce valuable protein outputs and address a number of environmental issues.

Health Risks and Safety Considerations

Although insects are beneficial for nutrition, possible health hazards should be carefully considered. Comprehensive safety study is necessary since some edible insects may result in neurotoxic responses that induce symptoms like photophobia (light sensitivity). People who are allergic to shellfish are especially at danger due to the cross-reactivity between insect proteins and crustacean allergens.

When insects are raised on agricultural waste that may contain pesticide residues, heavy metals, or mycotoxins, chemical contamination is a serious concern. Since insects may bioaccumulate toxic substances from polluted feed sources, the current usage of pesticides in Indian agriculture exacerbates these hazards.

Strategic Positioning

Compared to Western market techniques, India's strategy of concentrating on animal feed uses rather than direct human consumption may prove more effective. While meeting actual market demands in the poultry and aquaculture sectors, this posture takes advantage of current impediments to cultural acceptability. The nation has competitive advantages for expanding insect farming operations because to its plentiful food waste, ideal climate, and pre-existing agricultural infrastructure.

Research and Development Needs

Industry development still depends on ongoing research into insect nutrition, safety, and processing technologies. Additional uses for functional foods and nutraceuticals may become possible if traditional knowledge about medicinal characteristics is validated by science. The sector's long-term success will depend on investments made in consumer education, regulatory framework development, and food safety research.

Conclusion : Sustainable Solution or Niche Application?

According to the data, edible insects in India are a hopeful part of the nation's changing food chain with particular uses and restrictions rather than a straightforward fix or a potential hazard. Traditional methods show cultural acceptance in some areas, but there are major obstacles to general adoption, which could restrict insects to niche markets and uses. There is a major need for alternate protein sources because of India's protein crisis, which affects more than 70% of the population. But rather than completely replacing traditional proteins, the answer probably rests in specific uses, such as animal feed, aquaculture and specialty nutrition products. This strategy is supported by the success of businesses like Loopworm and Green Grahi that concentrate on business-to-business (B2B) markets rather than direct consumer goods.

In order to guarantee safety standards and give investors and entrepreneurs clarity, the regulatory framework needs to be developed immediately. Whether insects become a common source of protein or continue to be a niche use will depend on scientific study on conventional methods, safety measures and processing technology. Ultimately, rather than completely changing the protein landscape, edible insects in India seem destined for a specialized role in solving particular challenges *viz.* waste management, aquaculture feed and nutritional security in traditional communities. Instead of replacing current sources, their contribution to India's protein security will probably be evaluated based on how well they can turn trash into nutritious food while maintaining traditional knowledge and advancing sustainable development objectives.

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ENVIRONMENTAL DRIVERS OF APPETITE AND GROWTH IN AQUATIC SPECIES

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Introduction

The aquaculture industry is growing very rapidly because of demand for fish is at peak, as such the growth of fish is fully dependent on nutritional requirement filled by aquafeed, as 60 percentage of cost of production is aquafeed. Therefore, it is basic that you utilise aquafeed at its most efficient so as to minimise waste, as this will lead to significant financial losses arising from waste accumulation in water and the release of extra unionized ammonia from untouched aquafeed, which will be a major stressor for aquafarms. Orexigenic hormones play a crucial role in promoting appetite in all vertebrates, while anorexigenic hormones are connected to endocrine elements which reduce appetite and are in charge of fish's short- and long-term dietary performance. The Central Nervous System (CNS) and the Peripheral Nervous System, which include the gastrointestinal (GI) tract, pancreas, liver, and adipose tissue, provide information to central feeding centres through the vagus nerve or by directly acting through central receptors after passing through the blood-brain barrier (Brightman and Broadwell, 1976). Developing a thoughtful and effective aquaculture feeding system requires an accurate assessment of fish appetite. Fish appetite can be accurately reflected by residual bait (Hu *et al.,* 2021). According to studies, fish appetite and feeding quantity can be impacted by variations in water quality, involving temperature and dissolved oxygen saturation (Weiqiang Ni *et al.,* 2024).

Increase in water temperature tends to rise in metabolic rate of fish, therefore it's not vagueness to take change in temperature onto account as key study in effect of energy metabolism. The eating behaviours and food intake of fish have been observed to exhibit a circannual rhythm, which may be influenced by environmental changes such as seasonal shifts and temperature variations (Volkoff *et al.,* 2010). However, rise in temperatures increases in feed intake also based to studies on *Pleuronectus americans*, *Gadus morhua*, and *Salmo salar* (Bendiksen *et al.,* 2002; Kehoe AS & Volkof, 2008). Certain stream fish have been demonstrated to exhibit 30-60% increases in growth, hunger, and metabolism in response to a just 2ºC rise in water temperature (Morgan *et al.,* 2001). but rising temperatures at the optimum level which could be the change of fish in which all physiological functions at best that is optimum level for different species it could be different for tropical warm water species it is 25-32 degrees Celsius whereas for Coldwater fishes it is 14-18 degrees Celsius at this temperature range they could better grow, survive, and reproduce. Fish control their body temperature to maintain the ideal temperature required for survival. Every species has an ideal temperature range within which it can function, grow, reproduce, and metabolise (Dodson, 2005).

In comparison to terrestrial animals, fish utilise dissolved oxygen, that is quite tiny in comparison to oxygen found in air, to absorb into their circulation via their gills, (fish's breathing organ). Photosynthesis and air diffusion are responsible for the oxygen present in water. Oxygen ended in is based on the utilisation of fish and bacteria, and rising temperatures have revealed that oxygen will be reduced. For warmwater fish, the optimum dissolved oxygen concentration is 5 mg/litre; for Coldwater fish, the optimum dissolved oxygen concentration is 10 ppm; oxygen in the range of 1.0-5.0 mg/litre has sublethal effects and reduced growth, while 0.3-0.8mg/litre has been found to be lethal; at the optimum dissolved oxygen concentration, fish show better growth, feed intake, and disease resistance capacity.

Salinity is the concentration of all ions in water. It is measured as (Parts Per Thousand). For freshwater salinity is <0.5 ppt, for brackish water is in range of 0.5-35 ppt and for Seawater salinity is of >35 ppt. As fishes found in all waters which are mentioned above, so it's not wrong to consider that for these species this could be favoured range, It has been noticed that in favourable salinity range there could be better growth, At different salinities range feed intake can be vary, study conducted on *Tilapia rendalli* found that feed intake and growth of fish increased with salinity from 5 ppt to 10 ppt when the salinity increased to 15 ppt the feeding intensity was found to be restricted. (Kang'ombe & Brown, 2008).

Ammonia is a nitrogen-based compound present in water. It is mainly found in two forms, unionised and ionised; unionised ammonia is found to be more toxic, with the toxicity of this ammonia increasing with a rise in temperature and pH, whereas with higher oxygen and adequate phytoplankton concentration, the toxicity could be reduced. Appetite caused by exposure to ammonia is temporary, and prolonged exposure to ammonia alters the monoaminergic and corticotropin-releasing factor (CRF), which releases serotonin in the hypothalamus. This part of the brain is mainly associated with appetite. According to various research confirmed, that prolonged exposure of ammonia tends to loss of appetite and feed intake in European seabass (*Dicentrarchus labrax*) and in Rainbow trout (*Oncorhynchus mykiss*). (Ortega *et al.,* 2005& Dosdat, 2003).

Pollution, as we know, is the addition of harmful substance into a water body, which has an adverse effect on its existing flora and fauna. Growing human population tends to accelerate the desire to capture and utilise resources, controlling anthropogenic waste is a tough question to manage, the source of pollutants is mostly industrial, residential seawater, agricultural runoff, etc. Pollution of the environment will undoubtedly have an impact on native organisms. The sensory organs of fish are most susceptible to pollution because they have receptors elements that are exposed to the environment, such as olfactory, taste, and lateral line. It may impact the capacity to taste food, resulting in the consumption of improper food material. As a sensory organ is affected, it may also alter the way fish react to food stimuli, perhaps leading to the cessation of feeding. (Kasumyan, 2001).

Turbidity defines the cloudiness and muddiness of water. Turbidity found in water occurs from sand, clay particles, phytoplankton, bacteria, dissolved organic substances, and other microbes. Turbidity can be positive or negative depending on the reason the water became cloudy; when turbidity is caused through planktons, it is best; when turbidity is generated by clay and sand particles, it is undesirable because it clogs the gills of fish and may reduce dissolved oxygen, which we discussed earlier affects fish appetite. Turbidity might influence Fish depend on their eyesight to forage, which limits their ability to locate prey. Reducing development and survival, due to a more unclear environment, fish can reduce strike ability, increase search time, change food, and be hard to feel, which may indicate that not instantly digested food particles have been consumed.

pH is defined as the negative logarithm of H^+ ion concentration. The pH of water pH level indicates whether it is acidic or basic, which ranges from 0 to 14. Temperature and water pH also affect fish survival and growth. Water pH regulates numerous metabolic activities, and when fish are exposed to acidic or very alkaline water, ion loss in gills increases, resulting in increased mortality (Sapkale *et al.,* 2013). pH for tilapia culture has been determined to be in the range of 7-8 with satisfactory development and survival. The study reveals that pH has a substantial effect on the growth of Nile tilapia (*Oreochromis niloticus*) (Iqbal *et al.,* 2012). Here we show that the spontaneous firing rate of identified orexin neurons is profoundly affected by physiological fluctuations in acid and CO2 levels (Williams *et al.,* 2007)

Nutrients are critical not only for fish growth and health but also for regulating their feeding behaviour. The presence, balance, and quality of nutrients in the diet can either stimulate or suppress appetite in fish. Proteins are essential for tissue growth and maintenance. Certain free amino acids, such as leucine, arginine, and glutamate, act as feeding stimulants by activating taste receptors. Fish nutrient metabolism is the sum total of the biochemical reactions in life processes. Fish have small changes in genetic isozymes related with their habitat, but overall, cellular metabolism is similar among fish species. Most fish live in heat sinks, and their metabolism rates are determined by the temperature of the water. As a result, most fish have adapted enzyme systems to poikilothermic environments, and their genetic isozymes, while very similar in structure, combine with the same general substrates to achieve the digestion, absorption, and subsequent biochemical reactions required for energy generation and metabolite incorporation into cell functions. (Halver and Hardy, 2003).

Conclusion

Environmental factors play a crucial role in regulating the appetite of fish. Parameters such as water temperature, dissolved oxygen, pH, salinity, Nutrient, Turbidity and pollution directly influence the metabolic rate, physiological stress, and feeding behaviour of aquatic species. Optimal environmental conditions promote healthy feeding activity, growth, and survival, while unfavourable changes can suppress appetite, that affects on growth of the cultured animal. slow metabolism, and increase susceptibility to disease. Understanding and managing these environmental variables is essential in aquaculture and fisheries management to ensure maximum feed efficiency, improve fish welfare, and enhance production outcomes.

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INDIGENOUS TECHNICAL KNOWLEDGE (ITK) PRACTICES AGAINST *Scirtothrips dorsalis* HOOD AND *Myzus persicae* SULZ INFESTING CHILLI

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Abstract

An experiment was conducted to evaluate the efficacy of different Indigenous Technical Knowledge (ITK) practices along with one insecticidal treatment against chilli thrips (*Scirtothrips dorsalis* Hood) and aphid (*Myzus persicae* Sulz) during rabi season of 2014-2015 at District Seed Farm, A/B block, B.C.K.V., Kalyani, West Bengal. All the treatments were effective in reducing the population of aphidand thripsexcept the untreated control (UTC) plots. Among the ITK practices, 3 % NSKE and 3 % Panchagavya solution recorded the lowest mean number of aphids (1.91 & 2.30/ leaf respectively) and thrips (1.38 & 1.55/leaf respectively). The mean population of aphid in the remaining ITK practices ranged between 2.89 to 4.05/leaf while that of thrips ranged between 2.04 to 2.37/leaf. However, imidacloprid 17.8% SL @ 0.3 ml/ litre of water performed the best in comparison to ITK practices and recorded lowest mean number of aphids/leaf (1.28) and thrips/leaf (0.45) respectively. Different ITK practices contributed to the tune of 73.19 to 87.14% reduction over control in aphid population, while that for thrips population ranged between 60.11 to 77.28 %. In comparison, imidacloprid 17.8% SL recorded the highest % reduction in the population of both aphids (91.16) and thrips (92.25).

Keywords : Indigenous Technical Knowledge (ITK), chilli, *Scirtothrips dorsalis* Hood, *Myzus persicae* Sulz., NSKE, Panchagavya.

Introduction

Indigenous technical knowledge(ITK) is a community based functional knowledge system, developed, preserved and refined by generations of people through continuous interaction, observation and experimentation with their surrounding environment which has close links with the culture, civilization and religious practices of the communities (Pushpangadan *et al.*, 2002). It consists of technologies developed by farmers over decades of adjusting farming systems to local agro climatic and social conditions (Venkata Ramaiah and Rama Raju, 2004). The indigenous technical knowledge covers a wide range of subjects, viz. crop production, livestock rearing, natural resource management, food preparation, healthcare, insect pest management and many others (Vivekananda, 1993).It is transmitted through specific cultural and traditional information exchange mechanism. Singh (2007) mentioned that, it is maintained and transmitted orally through elders or specialists (breeders, healers etc.) and often to only a selected few people within a community.Location and culture specific, cost effective, locally manageable and sustainable, judicious application of plant and animal products either in raw or simple processed forms are important components of indigenous knowledge system (Chhetry and Belbahri, 2009). Most of these substances are safe, bio-degradable, less persistent, non-toxic and easily available in and around. Adivasis or the so-called aboriginal population in our country is considered the early settlers. They have been utilizing varieties of plant based products, crop residues and animal products for protecting their crop plants in the field and in storage of food grains. Some of the eco-based tribal pesticidal substances include kitchen ash, wood ash, red earth, cow dung, cow dung ash, cow urine, ragi husk, goat dung, goat urine, farmyard manure, *etc.* (Narayanasamy, 2006).

The use of neem for controlling insect infestation has been known in rural communities in India for a long time (Radha, 2013). Neem products affect the metamophosis of insects, their fecundity and have antifeedent effect (Dougnon *et. al*, 2013). One of the most important advantages of neem-based pesticides and neem insecticides is that they do not leave any residue on the plants (Lokanadhan *et al.*,2012). Some other ITK practices include dusting of ash in the fields by the farmers to kill small insects because it acts as a feeding barrier. It also acts as a repellent for oviposition. The practice is considered scientifically agreeable by 80% of the experts. Ash contains silica that has insecticidal properties. Ash also stimulates abrasion of the body waxes of insects (Kaur *et al*., 2008). Panchagavya is the single organic input that acts as a growth-promoter and immunity booster. As the name suggests, five products of the dairy-cow are usedin Panchagavya viz., cow dung, cow urine, buttermilk, milk and clarified butter (Bindumathi Mohan, 2008).

Prior to the advent of Green Revolution, Indian farming was largely based on indigenous technical knowledge of the farmers (Talukdar *et al*., 2012).Indigenous products have assumed greater importance in recent years all over the world dueto growing awareness of harmful effect of indiscriminate use of insecticides.Excessive use of synthetic insecticides has resulted in a series of problems like the development of insect resistance to insecticides, harm to other natural enemies of insects, toxic effects on plants and soil, etc. (Lokanadhan *et al*.,2012).

Therefore, Indigenous agricultural practices can play a key role in the design of sustainable and eco-friendly agricultural systems, increasing the likelihood that the rural populations will accept, develop and maintain innovations and interventions (Kaur *et al*., 2008). If an effort is made towards production of Indigenous Technical Knowledge (ITK) based products on cottage scale, it can be an economically viable option for sustainable development of eco-friendly pesticides/ insecticides (Lal and Verma, 2006). It is high time to acknowledge the urgent need for studies on indigenous technologies as because modernization of agriculture with rapid pace has resulted into gradual loss of their peculiar cultural heritage and great deal of valuable knowledge. Therefore, this experiment was conducted with the sole objective to find out such indigenous products which can prove to be a potential alternative or substitute to conventional pesticides in sustainable agriculture.

Materials and methods

The experiment was conducted at District Seed Farm, A/B block, B.C.K.V., Kalyani, West Bengal during rabi season of 2012-2013 in randomized block design. One month old healthy seedlings of "Suryamukhi" variety of chilli weretransplanted in 3x3 square metres plot at a spacing of 60x50 cms. The different treatment schedules were as follows: T_1: Untreated control, T_2:3% Panchagavya solution, T_3: 3%Neem Seed Kernel Extract (NSKE), T_4: Wood ash + turmeric powder @ 1:1, T_5:5 % neem soap solution, T_6:Tobacco decoction + neem oil +cow urine @ 1:2:1 and T_7:Imidacloprid 17.8% SL @ 0.3 ml/ litre of water.

Preparation of ITK materials

Panchagavya (T_2) : 5 Kg of fresh cow dung, 3 litre cow urine, 2 litre milk, 2 kgcurd, 500 gms ghee, 3 litres sugarcane juice, 3 litre tender coconut water, 12 ripe bananas and 2 litre toddywere mixed together in a clean earthen pot. The mixture was then kept in a shade covered with a plastic cover and was thoroughly stirred twice daily for 15 days using a wooden stick. 300 ml of the stock panchagavya was diluted in 10 litres of water to bring the required concentration to 3% prior to application in the field. (Sundararaman, 2009).

Neem Seed Kernel Extract (NSKE) (T_3) : 5 kg of clean neem seed kernel was ground into fine powder and was soaked in 10 litres of clean water. The mixture was kept overnight and filtered on thenext day with clean muslin cloth.300 ml of this extract was diluted in 10 litres of water to bring the required concentration to 3% prior to application in the field.

Wood ash+ turmeric (T_4) : wood ash was obtained by burning the dried wooden sticks and wooden waste available in the locality. Prior to application, turmeric powder and wood ash was mixed thoroughly at equal proportion.

Neem soap solution (T_5) : 500 ml of the neem oil was diluted in 10 litres of water along with 200 ml mild liquid soap as an emulsifier prior to application in the field.

Tobacco decoction + neem oil+ cow urine (T_6) : 500gms of tobacco leaf along with leaf stalk was cut into small pieces and soakedovernight in 5 litres of water.Tobacco decoction thus obtained was mixed with neem oil and cow urine at the ratio of 1:2:1 prior to application in the field.

The treatment comprising of wood ash + turmeric powder @ 1:1 (T_4) was applied by manual dusting whereas the liquid treatment formulations (T_2, T_3, T_5, T_6 snd T_7) were applied using knapsack sprayer at an interval of 15 days. The population count of the target pests were recorded one day before and 3, 7 and 14 days after each application. Both nymphs and adults of target pests were counted in situ from one top, middle and bottom leaves each from five randomly selected plants in each plot with the help of 10x hand lens. The data of the pest population were thus subjected to ANOVA after making necessary transformation.

Results and discussion

a) Effect of different ITK materials on Aphids,*Myzus persicae* Sulz (Table 1)

It can be seen that the pre treatment count of aphids varied from 11.00 to 12.11/leaf in different treatments. All the treatments were effective in reducing the population of aphid at 3, 7 and 10 days after application (DAA) except the untreated control (UTC) plots. At 10DAA of the first spray, maximum reduction in the population of aphid was noticed and the lowest number of aphids/leaf was recorded in T_7: imidacloprid 17.8 SL @ 0.3 ml/ litre of water (1.14/leaf) which was significantly different from all other treatments. It was followed by T_3: 3 % NSKE (2.60/leaf), T_2: 3 % Panchagavya solution (2.91/leaf) and T_4: wood ash + turmeric powder @ 1:1 (3.09/leaf) where$T_3$and T_2 were statistically at par with each other.Highest number of aphids/leaf was recorded in untreated control (14.16/leaf) followed by T_5: 5 % neem soap solution (3.56/leaf) and T_6: cow urine + neem oil + tobacco decoction @ 1:2:1 (3.42/leaf) which were statistically at par with each other.After the second spray, all the treated plots gave a significant reduction in the population of aphids at 3 DAA. However, lowest number of aphids/leaf was recorded at 10 DAA in T_7 (0.03/leaf) which was followed by T_3 (0.44) and T_2 (0.53/leaf) which were statistically at par with each other. The population of aphids reached its peak at 10 DAA in UTC (15.51/leaf). The present investigation is in line with the findings of Senthil kumar *et al.,* (2015) who reported the efficacy of 7% and 5% dilutedpanchagavya application against aphids in *Tectona grandis*.

b) Effect of different ITK materials on Thrips, *Scirtothrips dorsalis* Hood(Table 2)

The pre treatment count of thrips varied from 5.13 to 5.79 in different treatments. There was a significant reduction in the pest population in all the treated plots at 3 DAA. After the first spray, highest per cent reduction in the population of thrips was recorded at 10 DAA in T_7 (0.37/leaf) which was significantly different from all other treatments. Effective control of thrips was also recorded in T_3 (1.35/leaf) followed by T_2 (1.57/leaf) which was statistically at par with each other. T_5 and T_6 performed poorly in comparison to other treatments which recorded 2.40 and 2.13 thrips/leaf respectively and were statistically at par with each other while UTC proved to be the worst treatment with 6.19 thrips/leaf. After the second spray, the population of thrips at 3 DAA varied from 0.31/leaf in T_7 to 6.27/leaf in UTC. However, at 7 DAA, lowest number of thrips was recorded in T_7 (0.10/leaf) which proved to be the best treatment, while T_3 recorded 0.88 thrips/leaf which was followed by T_2 (1.05/leaf) and was statistically at par with each other. At 10 DAA, best result was obtained in T_7 which recorded 0.04 thrips/leaf followed by T_3 (0.86/leaf), T_2 (1.00/leaf) and T_4 (1.60/leaf). T_5 and T_6 were the least performing treatments with 1.93 and 1.89 thrips/leaf which were statistically at par with each other while UTC recorded 6.44 thrips/leaf. The results of the experiment has been supported by the findings of following authors. Singh *et al.,* (2021) reported the effectiveness of neem extract against thrips while Lal and Verma (2006) reported the effectiveness of chula ash sprinkling in vegetables against pests like aphids and thrips.

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Table 1: Effect of different ITK practices on the population of *Myzus persicae* Sulz. in chilli.

Treatments		PTC	First Application			Second Application			Mean	Mean % reduction over control
			3 DAA	7 DAA	10 DAA	3 DAA	7 DAA	10 DAA		
T_1	Untreated control	12.02	12.71	13.22	14.16	14.76	15.13	15.51	14.25	-
T_2	3 % Panchagavya solution	11.00	6.02	3.04	2.91	0.71	0.60	0.53	2.30	85.23
T_3	3 % Neem Seed Kernel Extract	11.53	4.59	2.93	2.60	0.37	0.55	0.44	1.91	87.14
T_4	Wood ash + turmeric powder @ 1:1	12.06	7.86	3.98	3.09	1.04	0.73	0.62	2.89	79.65
T_5	5 % neem soap solution	11.34	10.13	5.91	3.56	2.02	1.44	1.24	4.05	73.19
T_6	Tobacco decoction + neem oil + cow urine @ 1:2:1	12.11	10.71	4.51	3.42	1.46	0.98	1.04	3.69	73.91
T_7	Imidacloprid 17.8% SL @ 0.3 ml/ litre of water	11.83	3.51	2.49	1.14	0.40	0.12	0.03	1.28	91.16
C.D. at 5%		-	2.06	1.07	0.44	0.36	0.25	0.36	-	-
S.Em±		-	0.68	0.35	0.14	0.12	0.08	0.12	-	-

DAA: Days after application,PTC: Pre-treatment count

Table 2: Effect of different ITK practices on the population of *Scirtothrips dorsalis* Hood in chilli.

Treatments		PTC	First Application			Second Application			Mean	Mean % reduction over control
			3 DAA	7 DAA	10 DAA	3 DAA	7 DAA	10 DAA		
T_1	Untreated control	5.61	5.96	6.14	6.19	6.27	6.39	6.44	6.23	-
T_2	3 % Panchagavya solution	5.13	2.34	2.18	1.57	1.14	1.05	1.00	1.55	72.79
T_3	3 % Neem Seed Kernel Extract	5.47	2.31	1.95	1.35	0.92	0.88	0.86	1.38	77.28
T_4	Wood ash + turmeric powder @ 1:1	5.55	2.67	2.72	1.89	1.70	1.65	1.60	2.04	66.90
T_5	5 % neem soap solution	5.35	2.88	3.06	2.40	2.00	1.97	1.93	2.37	60.11
T_6	Tobacco decoction + neem oil + cow urine @ 1:2:1	5.79	2.80	2.97	2.13	1.94	1.91	1.89	2.27	64.70
T_7	Imidacloprid 17.8% SL @ 0.3 ml/ litre of water	5.23	0.92	1.08	0.37	0.16	0.10	0.04	0.45	92.25
C.D. at 5%		-	0.39	0.20	0.29	0.31	0.23	0.27	-	-
S.Em±		-	0.13	0.06	0.09	0.10	0.07	0.09	-	-

DAA: Days after application, PTC: Pre-treatment count

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FARM MECHANIZATION: THE ROLE OF AI AND ROBOTICS IN PRECISION AGRICULTURE

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Introduction

Agriculture is undergoing a silent revolution. From the plough to tractors, mechanization has always shaped farming. But today, as the world enters the **Fourth Industrial Revolution (Industry 4.0),** Agriculture too is embracing **Farm Mechanization.** This new wave integrates **Artificial Intelligence (AI), Internet of Things (IoT), Drones, Robotics, and Big Data** into precision farming. The goal is simple yet transformative: produce more food with fewer resources while adapting to climate change and labour shortages. In India, where agriculture employs nearly **42% of the workforce** but productivity remains below the global average, mechanization promises to boost efficiency, profitability, and sustainability.

The Evolution of Farm Mechanization:

1. **Mechanization 1.0 (Early tools):** Animal-drawn ploughs, simple irrigation, manual harvesting.
2. **Mechanization 2.0 (Industrial era):** Tractors, threshers, chemical sprayers revolutionized productivity.
3. **Mechanization 3.0 (Green Revolution):** High-yield seeds, combine harvesters, fertilizer spreaders increased scale and intensity.
4. **Mechanization 4.0 (Present):** Digital agriculture using AI, robotics, drones, and sensors—where machines not only do work but also “think,” “see,” and “decide.”

Key Technologies Driving Farm Mechanization:

1. Artificial Intelligence (AI)

AI enables machines to “learn” from data and make decisions. In agriculture, AI is used for:

- **Predictive analytics:** Forecasting yield, disease outbreaks, and weather risks.
- **Image recognition:** Drones or cameras detecting pests, nutrient deficiencies, or weed patches.
- **Decision support:** Recommending optimal sowing time, irrigation schedules, or fertilizer doses.

Example: The ICAR–Central Research Institute for Dryland Agriculture (CRIDA) is testing AI-based crop models to predict drought impacts and suggest adaptive practices.

2. Robotics in Agriculture

Agricultural robots, or "agribots," are transforming field operations:

- **Autonomous tractors:** Self-driving tractors guided by GPS, reducing labor dependency.
- **Robotic weeders:** Using computer vision to identify and mechanically remove weeds.
- **Fruit harvesters:** Robots with sensors and soft grippers that pluck ripe fruits without damage.
- **Planting drones:** Aerial drones that drop seed pods with precision in reforestation and large farms.

Example: In Europe, strawberry-picking robots are already operating commercially. In India, startups are developing **AI-powered cotton-picking machines** to reduce drudgery for women farm workers.

3. Drones and Aerial Imaging

Drones have become the "eyes in the sky" for farmers:

- **Crop monitoring:** Detecting early stress or pest infestations.
- **Aerial spraying:** Applying fertilizers and pesticides uniformly, reducing human exposure.
- **Mapping fields:** Creating 3D maps to analyze soil and water variability.

India in action: The Government of India approved **drones for spraying nano-urea** developed by IFFCO, cutting fertilizer wastage and ensuring precise application.

4. Internet of Things (IoT) & Sensors

Smart sensors measure soil moisture, pH, nutrient status, and even micro-climate conditions. When linked to AI platforms:

- Irrigation is automated through drip systems.
- Fertigation is precisely matched with crop needs.
- Farmers receive real-time alerts on mobile apps.

Example: ICAR–IIFSR Modipuram has developed IoT-based systems for precision irrigation scheduling in vegetables.

5. Big Data and Cloud Platforms

Farm Mechanization thrives on data. Data from satellites, drones, sensors, and markets feed into cloud platforms that analyze patterns and predict outcomes. Farmers, policymakers, and agri-businesses can use these insights for smarter decisions.

Benefits of Mechanization:

1. **Higher Efficiency:** Reduced input waste, optimized irrigation and fertilizer use.
2. **Labor Saving:** Robots and drones reduce dependence on scarce farm labor.
3. **Sustainability:** Less chemical use, lower carbon footprint.
4. **Higher Yields:** Timely interventions improve crop health.
5. **Farmer Welfare:** Reduces drudgery, especially for women and smallholders.

India's Readiness and Policy Push:

- **Custom Hiring Centres (CHCs):** Promoted by ICAR and state governments, offering costly machinery on rental basis.
- **Digital Agriculture Mission 2021–2025:** Focus on AI, block chain, and drones.
- **Sub-Mission on Agricultural Mechanization (SMAM):** Providing subsidies for precision machinery.

- **Startup Ecosystem:** Indian agri-tech startups like TartanSense and Fasal are deploying AI-driven robots and decision-support tools for farmers.

Challenges Ahead:

Despite potential, barriers remain:

- High cost of AI/robotics machines.
- Lack of digital literacy among smallholders.
- Connectivity issues in rural areas.
- Need for localized solutions—Indian farms are smaller and more fragmented compared to Western farms.

The future plans

The future of Farm Mechanization depends on:

- **Affordable innovations** for small and marginal farmers.
- **Public-private partnerships** to scale AI tools.
- **Training through Krishi Vigyan Kendras (KVKs)** and Farmer Producer Organizations (FPOs).
- **Integration with climate-smart practices** to ensure resilience.

Conclusion

Farm Mechanization is not just about machines it's about **intelligent farming systems**. By merging AI, robotics, and digital tools with traditional knowledge, agriculture can become more precise, sustainable, and resilient. For India, this is an opportunity to leapfrog into the future is boosting farmer incomes, ensuring food security, and making agriculture attractive to the next generation.

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FOOD FORESTS: REIMAGINING INDIA'S NUTRITIONAL SECURITY

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Abstract
Food forest or Community food garden is a concept of integrating various tree species that includes fruit trees like citrus, guava, mango etc. along with medicinal plants and kitchen garden on an uncultivated or barren land to produce food, generate supplementary income, utilize resources and enhance biodiversity. Through the execution of this concept we can ensure year round supply of fresh fruits, vegetables and other produces to meet health and nutritional requirement. This model is low cost, climate resilient and community driven which makes it one of the best practical intervention suitable for both for rural and urban areas. Beyond food security, food forests contribute to ecological gains like improved soil health, water conservation and carbon sequestration, positioning them as holistic tools for sustainable development. This article throws light upon the concept of food forest, how it works, its benefits and how this approach ensure nutritional security.

Keywords : Food forests, Nutritional security, Biodiversity, Climate resilience, Miyawaki fruit forest.

What is a food forest?
A food forest is a diverse, multi-layered agricultural system designed to mimic a natural forest ecosystem to produce food sustainably with minimum human inputs. It has edible perennial plants in different vertical layers comprising of canopy, understory, shrubs, herbs, ground cover and vines. These layers of plants thrive together as a self-sufficient, resilient agroecosystem that yields plethora of nutritious fruits, nuts, vegetables and herbs (vegetable and medicinal).

Fig. 1: Illustration of a food forest.

Features of food forest

1. It can be established on a barren and wasteland without compromising agricultural area.
2. Established as an urban food garden, community forest on a small to large area.
3. Self-sustaining and regenerative natural ecosystem.
4. Yields produce of fruits, vegetables, nuts round the year.
5. Needs proper designing and landscaping for better establishment.
6. Must be established on principles of natural farming.
7. Crops and trees should be grown in their favourable climatic and agroecological situation for better yield.

Elements of a nutritive food forest

A nutritive food forest feels like a nutrition garden, where fruit trees, leafy greens, vegetables, and pulses grow side by side to provide families with fresh, wholesome, chemical-free food all year round. It also nurtures medicinal herbs, millets, and root crops, making it healthy. Following table describes in detail about the elements of a nutritive food forest.

Sr. No.	Plant	Nutritional properties	Layer
1.	Moringa tree	Source of calcium, iron, Vitamin A, B and C, proteins, antioxidants	Canopy
2.	Jamun tree	Useful for diabetic patients	Canopy
3.	Coconut tree	Coconut water rich in antioxidants, minerals, cures kidney stones	Canopy
4.	Mango tree	Vitamin A and C, fiber, antioxidants and minerals like potassium	canopy
5.	Banana	Calcium, Vitamin B6, potassium, fiber	Shrubs
6.	Lemon	Vitamin C, fiber, potassium, maintains electrolytic balance of body	Shrubs
7.	Papaya	Vitamin A, iron, fiber, good for diabetic patients	Shrubs
8.	Chilli	Vitamin C, A and K, potassium, low in calories, antioxidants	Shrubs
9.	Tomatoes	Vitamin C and K, potassium, Vitamin B, fibers and antioxidants	Shrubs
10.	Coriander	Antioxidants, fiber, Vitamin A and C	Herbs
11.	Spinach	Vitamin A and K, iron, calcium	Herbs
12.	Broccoli	Vitamin C and K, fiber, folic acid, iron, low in fats	Herbs
13.	Beetroot	Vitamin B and C, iron, potassium, fiber, antioxidants	Roots
14.	Yam	Vitamin C, potassium, magnesium, fiber	Roots
15.	Carrot	Vitamin A and K, calcium, magnesium, potassium	Roots
16.	Cucumber	Vitamin C and K, low-calorie, hydrating food	Vines
17.	Bitter gourd	Vitamin A and C, controls blood sugar level	Vines

The above table presents a small list of plants that can be incorporated into a food forest. It is possible to incorporate more species than the listed in a particular food forest, based on the climatic suitability of the crops in a particular region.

Need and importance of food forest

Since the beginning of the civilization and even before that, forests have been the prime provider of food to the living beings. Before Neolithic age (the era when the humans started practicing agriculture and settled civilization), early humans depended entirely on the forest foods – leaves, roots, fruits, berries – to meet their food and nutritional requirements. Along with the food products, forests have been providing medicinal products, honey produced by honey bees in the forests, non-conventional foods like mushrooms growing in the forest ecosystem are in huge demand in the world for their medicinal and nutritional properties. Ayurveda, Indian traditional medicine system, emphasizes on the consumption of forest based foods and medicinal products to live a healthy life. Today, in India, only small percentage of population are dependent on forests for food and worship them as an expression of gratitude to nourish them. Indigenous tribes like Baigas in Madhya Pradesh, Gonds in Jharkhand and Chhattisgarh, Paikas in Odisha and various others in the different states are nurturing forest based ecosystems to nourish themselves.

India is suffering from the double burden of malnutrition that is a part of population is undernutrition with deficiency of nutrients and other part if it is obesed due to excess of nutrients. According to National Family Health Survey Report (NFHS-5, 2019-21), child malnutrition is reported as 36.00 per cent of the children under 5 are stunted, 19.00 per cent are wasted, 32.00 per cent are underweight, 03.00 per cent are overweight and 67.00 per cent suffers from anaemia. Among adults, 16.00 per cent males and 19.00 per cent females suffer from under-nutrition, 23.00 per cent males and 24.00 per cent females suffer from over-nutrition and 25.00 per cent males and 67.00 per cent females suffer from anaemia. Therefore, to combat the malnutrition and suffice the nutritional needs of the ever growing population, we should grow and maintain food forests.

Benefits of food forest

1. Harness food and nutritional security of individuals.
2. Fulfils the balanced diet needs.
3. Food forest act as unit of carbon sequestration.
4. Create green spaces in urban areas (Miyawaki forests).
5. Regenerative in nature – soil and water conservation.
6. Maintains ecological biodiversity.
7. Improves microclimate of an area.
8. Surplus produce can be sold into market to get supplementary income.
9. Can be turned into an agrotourism enterprise for additional income from it.

Below mentioned are some existing food forests in India

1. Aranyaani food forest, Madhya Pradesh
2. Aanandaa Permaculture Farms, Haryana
3. Solitude Farm, Auroville, Puducherry
4. Indraprastha Farms, Kalalavadi, Karnataka

Mr. Mckenzie, the owner of Solitude Farm, Auroville regularly conducts workshops on his farm for the people to learn permaculture practice and encourage them to grow their own food forests back in their hometowns and villages.

Food Forests in Government Schools

The introduction of food forests in and around the government schools can have a transformative effect. By linking this approach with the Mid-Day Meal Schemes, the schools can ensure a steady supply of fresh vegetables, fruits, and green leaves like spinach, *Amaranthus,* etc., to enhance the nutritional value of the meals prepared and served to the students in the schools. Such initiatives not only reduce dependency on external food supply chains but also create environmental awareness, gardening skills, and healthy food habits among students. Food forests in school premises can double as learning laboratories, where children engage with science, ecology, and nutrition in a practical, hands-on manner—nurturing both their bodies and minds.

Miyawaki fruit forest

A Miyawaki fruit forest is a high density plantation of fast-growing, native fruit-bearing trees designed to mimic natural forests. In a Miyawaki fruit forest, species like mango, guava, papaya, jamun, and banana are planted closely together alongside shrubs and climbers. Using the Miyawaki method, these forests grow rapidly into self-sustaining ecosystems within 2–3 years, providing year-round fruits, improving soil fertility, supporting pollinators, and enhancing biodiversity. When established in schools or communities, they not only supply fresh, nutritious food but also create green spaces for learning, environmental awareness, and healthier lifestyles.

Fig. 2: Miyawaki fruit forest model

Strategies to encourage people to take up food forests

1. Sensitization of children at young age itself to encourage them to live sustainable life – can be done through school picnics to nearby permaculture farms.
2. Motivating village communities to takeup permaculture on a piece of land of their own village – initiatives like "One Village One Food forest" can be driven.
3. Civil societies, NGOs, volunteer groups can play an active role in promoting food forests.
4. Village women and Self Help Groups can lead in growing and maintaining a village food forest.
5. Youth and students along with support of local governing bodies should convert urban wasteland into a fulfilling food forest.

Conclusion

The idea of food forests as a solution to nutritional security is truly compelling. Instead of relying on a system that often feels disconnected from the land, this approach taps into a natural and cyclic way of growing food. It integrates various kinds of tree species from fruit bearing to medical plants. It's about bringing life back to the soil and putting nutritious, local food directly into the hands of those who need it the most. This is a suitable method to replenish the waste lands and use it productively to meet the requirements of the local community.

By integrating this approach into schools , in particular to goverment schools makes it even better model to ensure self sufficiency and proper utilisation of available spaces productively. Through

Miyawaki fruit forest model, the schools can reduce the dependency on external markets to purchase fruits and vegetables to prepare mid day meals as most of them can be grown within the school compound, utilising the available land area.

Through this model, we can conserve both biodiversity and also ensures nutrition to the growing population of India.It's a hands-on education in sustainability that could change their lives, and in turn, the future of the planet. Through this approach, we can feed not just hunger, but also the hope for a sustainable future. It's a vision of a future where we live in harmony with the environment, where communities are resilient, and where everyone has access to the nourishment they need to thrive.

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FOODSCAPING: BLENDING BEAUTY AND EDIBILITY IN MODERN LANDSCAPES

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Introduction

Foodscaping, often referred to as *edible landscaping*, is not merely a fleeting gardening trend and it represents a **transformative lifestyle revolution** that is redefining how we think about food production, aesthetics, and sustainability. Unlike conventional gardens that separate ornamental flowers from vegetable plots, foodscaping brings them together in a single, harmonious landscape. It combines the elegance of flowering plants with the productivity of fruits, vegetables, and herbs, ensuring that every corner of a yard, balcony, or even an urban rooftop can serve a dual purpose is **pleasing the eye while feeding the body**. Imagine stepping outside and being welcomed by vibrant marigolds that deter pests, alongside thriving kale with its deep green leaves; a border of lavender buzzing with pollinators; or a pergola draped in grapevines that not only provide shade but also yield juicy clusters of fruit. Foodscaping is as much about **aesthetic enrichment** as it is about **nutritional empowerment**. It transforms unused lawns into living pantries, promotes biodiversity by attracting beneficial insects, and contributes to climate resilience by making urban spaces greener and more self-sufficient. At its core, foodscaping reflects a growing movement in agriculture and horticulture that emphasizes **resource efficiency, ecological balance, and food security**. As urban populations rise and land availability shrinks, this approach offers a creative and sustainable way to integrate food production into everyday landscapes. By blurring the line between beauty and utility, foodscaping reminds us that our surroundings can nourish not just our senses, but also our plates.

The Concept of Food scaping

Foodscaping is more than simply mixing vegetables and flowers. It is the **artful intersection of horticultural science, landscape design, and agroecology**. At its heart lies a simple yet powerful idea: every space, whether a sprawling backyard, a modest balcony, or even a community park, can serve both **practical and aesthetic purposes**. Instead of treating vegetable patches as purely utilitarian and ornamental gardens as purely decorative, foodscaping blends the two into a **multifunctional landscape**. This approach ensures that **space is never wasted** a border of chili plants might frame a lawn, spinach could fill gaps between roses, and dwarf fruit trees could line a walkway while providing seasonal harvests. Such designs not only look appealing but also enhance

biodiversity, creating microhabitats for pollinators, beneficial insects, and birds. By weaving edibility into ornamental landscapes, foodscaping encourages **food self-reliance**, allowing families to harvest fresh produce just steps from their door without compromising visual beauty.

Scope of Foodscaping is Trending in 2025:
The rising popularity of foodscaping in 2025 is no coincidence—it reflects **changing lifestyles, environmental priorities, and cultural shifts**:

- **Urban space constraints**: With shrinking backyards and apartment living becoming the norm, multifunctional landscapes are essential. Foodscaping maximizes limited space, ensuring that even small patches of soil or vertical walls contribute to both beauty and nutrition.
- **Health consciousness**: More people are prioritizing **fresh, chemical-free, and nutrient-dense foods**. Growing your own herbs, vegetables, and fruits through foodscaping provides complete control over cultivation methods, offering peace of mind about what goes onto the plate.
- **Environmental benefits**: Foodscaping supports **pollinator populations** through diverse flowering plants, reduces dependence on transported food, and cuts down on **food miles**, thus lowering carbon footprints. A single foodscaped garden can become a small but meaningful contribution to ecological sustainability.
- **Social media inspiration**: Platforms like Instagram, Pinterest, and YouTube have amplified the movement. Pictures of vibrant, edible landscapes are inspiring urban dwellers and young gardeners alike to replicate these designs, making foodscaping not just a practice but also a **global trend in lifestyle aesthetics**.

Design Principles of a Successful Foodscape:
Creating a thriving foodscape is both a science and an art. It requires thoughtful planning so that the space remains **visually stunning and agriculturally productive** throughout the year. A well-designed foodscape is not just a patchwork of plants—it's a carefully choreographed landscape that balances structure, beauty, and yield. Some guiding principles include:

Layering and Structure
It's Just like a natural forest, a successful foodscape thrives on layers. Fruit trees such as guava, papaya, or lemon can form the upper canopy, providing shade and anchoring the design. Beneath them, shrubs and herbs like curry leaf, mint, or rosemary can occupy the middle tier, while ground-level crops like leafy greens, edible flowers, or seasonal vegetables to fill the lowest layer. This vertical arrangement maximizes sunlight capture, optimizes space, and ensures that every inch contributes to productivity.

Color and Texture Harmony:
A foodscape should delight the eyes as much as it feeds the body. Mixing foliage textures and smooth spinach leaves with frilly kale or glossy curry leaves alongside rainbow chard it also creates natural visual interest. Seasonal blooms, whether it's the fiery orange of nasturtiums or the soft hues of hibiscus, provide year-round appeal. By thoughtfully combining colors and textures, the garden remains vibrant in every season.

Plants for Indian Conditions:
One of the most exciting aspects of foodscaping is the **sheer diversity of plants** that can be used. In India, with its wide range of climates, gardeners have the advantage of choosing from a rich palette of fruit trees, herbs, vegetables, and edible flowers.

- **Ornamental Vegetables**: Varieties like purple kale, rainbow chard, and cherry tomatoes bring bursts of colour to the garden while adding gourmet flair to the kitchen.
- **Fruit Trees:** Guava, lemon, pomegranate, fig, and papaya not only provide nutrition but also serve as structural elements, offering shade and focal points in the landscape.
- **Edible Flowers**: Hibiscus, rose, nasturtium, and banana blossom can brighten up garden beds and salads alike, proving that beauty and taste go hand in hand.
- **Herbs**: Tulsi, mint, lemongrass, coriander, and curry leaf are staples in Indian kitchens. Their fragrance enhances the sensory appeal of the garden while making fresh seasoning readily available.

Integration with Urban Horticulture Initiatives:

Foodscaping is increasingly being recognized as a practical solution to urban food and environmental challenges. In India, **ICAR-Indian Institute of Horticultural Research (IIHR), Bengaluru**, and **ICAR-Directorate of Floricultural Research (DFR), Pune**, have been actively promoting the concept of edible landscaping. Through **demonstration gardens, training programs, and awareness drives**, these institutes are showing city dwellers how functional food scapes can be both productive and visually appealing.

Benefits to People and the Environment:

Foodscaping is more than a gardening technique—it is a **holistic approach** to sustainable living that touches multiple dimensions of human and environmental well-being:

- **Nutritional Security**: Access to **fresh, chemical-free produce** right at the doorstep improves diet quality and reduces dependency on external markets.
- **Biodiversity Enhancement**: Mixed plantings create habitats for pollinators, birds, and beneficial insects, strengthening ecological resilience.
- **Reduced Environmental Impact**: By producing food locally, foodscapes reduce the carbon footprint linked to **transportation, packaging, and cold storage**.
- **Aesthetic & Mental Well-being**: Studies show that **green, edible spaces reduce stress, improve mental health, and foster community interaction**. A foodscape, therefore, is not just a garden but also a **wellness hub**.

Living Models of Foodscaping:

- **Bengaluru Rooftop Foodscape**: On a 200 m^2 terrace in the heart of the city, a layered edible garden was created using vertical planters, raised beds, and trellises. This foodscape now produces nearly **120 kg of vegetables annually**, including tomatoes, spinach, and gourds, while doubling up as a peaceful relaxation zone for the residents. The space demonstrates that productivity and recreation can coexist in the same urban corner.
- **Kerala Homestead Garden**: In rural Kerala, a traditional homestead was redesigned with **banana plants for fruit, pepper vines for spice, and hibiscus hedges for beauty and edibility**. The model not only supplies the family with a variety of daily essentials but also provides **supplementary income** through the sale of surplus produce. This design reflects how foodscaping can adapt to cultural preferences while maintaining ecological balance.

Conclusion

Foodscaping is more than a gardening trend and it is a **philosophy of sustainable living**. By blending beauty with utility, it transforms ordinary spaces into landscapes that are productive, resilient, and visually appealing. From rooftops in cities to homesteads in villages, foodscaping shows that every patch of land can provide nourishment while enriching the environment.

EDIBLE WALL GARDEN

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GENDER MAINSTREAMING IN FISHERIES: UNLOCKING THE POWER OF EQUALITY

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Abstract
This article examines the significance of gender mainstreaming in the fisheries sector, focusing on reducing gender disparities to improve productivity, enhance livelihoods, and ensure sustainability. It highlights women's vital contributions in areas such as fish processing, marketing, and resource management, emphasizing that empowering women fosters sustainable practices and drives economic growth. The article discusses key challenges, including cultural barriers, inadequate data, and the need for stronger policies to promote equality. Drawing on case studies from Tamil Nadu and Odisha, it showcases successful gender-inclusive initiatives that have empowered women, strengthened community participation, and demonstrated how gender-sensitive approaches benefit fisheries and coastal development.

Key words: Gender, Gender equality, Gender Mainstreaming, fisheries, Women empowerment

Introduction
Gender equality is crucial not just for social justice but also for achieving sustainable development in various sectors. One area where gender equality is not only a moral issue but also a practical necessity is the fisheries sector. While much of the focus in fisheries management has been on environmental sustainability, gender equality has often been overlooked. By addressing the gender disparities in fisheries, we can enhance productivity, improve livelihoods, and contribute to the sustainability of fisheries. This article delves into the concept of gender mainstreaming in fisheries, highlighting its importance, benefits, and the challenges faced in its implementation.

Gender Mainstreaming in Fisheries
Gender mainstreaming is the process of integrating gender perspectives into all policies, programs, and activities. In the context of fisheries, this involves ensuring that the roles, needs, and challenges of both men and women in the sector are recognized and addressed in policies, management strategies, and programs. While the fisheries sector is often seen as predominantly male-dominated, especially in activities like fishing and selling, women play an equally vital role in activities such as fish processing, marketing, and managing household-based fisheries (FAO, 2020). However, their contributions are often invisible and undervalued. Gender mainstreaming aims to correct this by providing equal opportunities and recognition for both genders in all areas of fisheries, from resource management to decision-making processes.

The Gender Gap in Fisheries
In many parts of the world, women are disproportionately represented in low-paid, informal work related to fisheries, such as fish processing and trading. These tasks, though essential to the industry, are often not recognized as formal economic contributions. According to the Food and Agriculture Organization (FAO), women's roles in fisheries are underreported, and gender inequalities persist in

the allocation of resources, benefits, and decision-making power (FAO, 2019). One of the key barriers women face in fisheries is access to financial and technical resources. Women are often excluded from training programs, fishing technologies, and credit facilities. For example, women in small-scale fisheries often lack access to modern fishing equipment, which limits their productivity and income. Cultural norms in many communities also restrict women's mobility and their ability to engage in high-value fisheries activities.

Why Gender Mainstreaming Matters

Gender mainstreaming in fisheries is critical for several reasons:

Fig: Women's involvement in seaweed farming

Empowerment of Women

Empowering women in the fisheries sector ensures they have equal access to resources, opportunities, and decision-making power. This inclusion leads to better resource management and economic development. Women often contribute to sustainable practices, such as responsible fishing and preserving fish stocks, due to their focus on long-term family welfare and food security. By giving women leadership roles, their perspectives lead to more inclusive decision-making, promoting both gender equality and more effective resource management.

Sustainable Development

Gender equality is crucial for sustainable development, particularly in fisheries. Women tend to prioritize environmental sustainability and community well-being, focusing on practices that protect natural resources for future generations. Their involvement in fisheries management ensures more sustainable outcomes by integrating diverse perspectives, which strengthens both environmental conservation and social equity. Women's leadership in managing resources helps communities adapt to challenges like climate change, ensuring long-term sustainability.

Economic Growth

Gender mainstreaming boosts economic growth in the fisheries sector. By empowering women, the sector taps into underutilized human resources, leading to increased productivity. Women often bring innovative solutions, such as new marketing methods or diversifying aquaculture, which boosts economic output. Furthermore, women’s participation generates employment opportunities and contributes to the local economy, as they reinvest income in their families. Gender equality in the workforce fosters broader economic growth, benefiting the entire community.

Increased Productivity and Innovation

Gender-sensitive approaches in fisheries management can enhance innovation. For example, women-led initiatives in fish processing and marketing have been found to increase the quality and diversity of products, benefiting both local economies and global markets (UN Women, 2020).

1. **Improved Food Security**: Women in fisheries often focus on household nutrition, making them key players in food security. By ensuring that women have access to the resources they need, we can improve nutrition and reduce hunger in fisheries-dependent communities (World Bank, 2021).
2. **Community Resilience**: When women are empowered within fisheries management, communities become more resilient to external shocks, such as climate change, overfishing, and economic downturns. Women's leadership in resource management contributes to more sustainable fishing practices and better environmental outcomes.

Challenges and Solutions

Despite the clear benefits of gender mainstreaming in fisheries, several challenges remain:

- **Cultural Resistance**: In many fishing communities, traditional gender roles are deeply ingrained. Women's contributions are often undervalued, and men are typically viewed as the primary decision-makers.
- **Lack of Data**: Gender-disaggregated data is crucial for understanding the specific needs and contributions of women in fisheries. However, such data is often sparse, making it difficult to design effective gender-sensitive policies.

Solutions:

Policy Changes: Governments and organizations need to implement policies that specifically address gender disparities in fisheries. For example, the FAO's Gender and Fisheries Program encourages governments to create laws that ensure equal access to resources, training, and technology for women (FAO, 2020).

Training and Education: Providing targeted training for women in both technical skills (like modern fishing techniques) and leadership skills (like resource management) can help women become more involved in decision-making and management roles.

Inclusive Decision-Making: Gender mainstreaming in fisheries requires the active inclusion of women in decision-making processes at local, national, and international levels. This includes women's representation in fishery management boards and advisory councils.

Case Studies

Seaweed Farming in Ramanathapuram, Tamil Nadu

In Ramanathapuram district, Tamil Nadu, a notable initiative has empowered women through seaweed farming. Self-Help Groups (SHGs) of women have been engaged in cultivating *Kappaphycus alvarezii*, a commercially valuable seaweed (Vipinkumar et al., 2020). The project has led to increased women's participation in site selection, seeding, drying, and packing, traditionally male-dominated tasks. An assessment using an "Empowerment Index" revealed significant improvements in women's access to resources, decision-making, and economic independence. This initiative not only enhanced women's livelihoods but also contributed to sustainable coastal resource management.

Ornamental Fish Farming in Odisha

In Bhatunia, Keonjhar District, Odisha, the ICAR-Central Inland Fisheries Research Institute established an ornamental fish farming unit to empower tribal women (Parida et al., (2022). This initiative provided women with training in fish breeding and farming, leading to improved economic status and self-reliance. The project aligns with the Pradhan Mantri Matsya Sampada Yojana

(PMMSY), aiming to enhance fish production and generate employment. The success of this model has encouraged replication in other regions, demonstrating the potential of small-scale aquaculture in uplifting women in rural areas.

Conclusion

Gender mainstreaming in fisheries is not just a matter of equality; it is a crucial strategy for improving the sustainability and resilience of the fisheries sector. By ensuring that both women and men have equal access to resources, decision-making, and opportunities, we can unlock the full potential of the fisheries sector. This, in turn, will contribute to more sustainable resource management, stronger communities, and improved livelihoods for all.

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MECHANIZATION OPTIONS AND ECONOMIC ANALYSIS OF PADDY THRESHING IN NORTHEAST INDIA

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Abstract
Rice cultivation remains a strategic pillar of agriculture and rural economy in Northeast India, yet the selection of paddy threshing methods (manual, semi-mechanized, or mechanized) is shaped by economic constraints, labour trends, landholding patterns, and ergonomic concerns. This comprehensive review evaluates the cost-effectiveness, labour dynamics, and socio-economic implications of these approaches, incorporating recent insights on adoption of mechanization, comparative efficiency, ergonomic outcomes, and labour-saving technologies. Evidence from regional and national studies highlights that context-sensitive adoption of mechanized and ergonomic threshing solutions can enhance productivity, reduce drudgery, and improve livelihoods, while preserving environmental and cultural sustainability.

Keywords : Paddy threshing, mechanized agriculture, ergonomics, Northeast India

Introduction

Rice production in Northeast India underpins food security in Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura; yet the stage of paddy threshing is often challenged by labour shortages, economic pressures, and the region's fragmented land structure. Traditional methods, although rooted in local conditions and often supported through communal labour, are increasingly strained by demographic shifts, rising rural wages, and the need for efficiency. Contemporary research demonstrates that both mechanization and ergonomic innovations can transform threshing practices, labor requirements, and the broader socio-economic landscape.

Traditional Threshing Methods

Indigenous techniques still account for substantial threshing activity, relying on locally available resources:

- **Plank beating and bamboo mats:** Widely used for sticky or traditional rice varieties, these approaches facilitate small-batch work and minimize external input costs, though labour intensity is high and output efficiency limited.
- **Foot trampling:** Collective trampling, sometimes involving livestock, is not only physically demanding but also socio-cultural significant during harvest periods. Ergonomic studies indicate persistent musculoskeletal risks with such labor, urging for safer and more productive alternatives (Singh H. J. *et al.,* 2024).
- **Flails and bullock treading:** While flail beating offers control and adaptability to weather, bullock-led trampling enables higher throughput but requires careful handling to reduce grain breakage (Goswami, 2020).

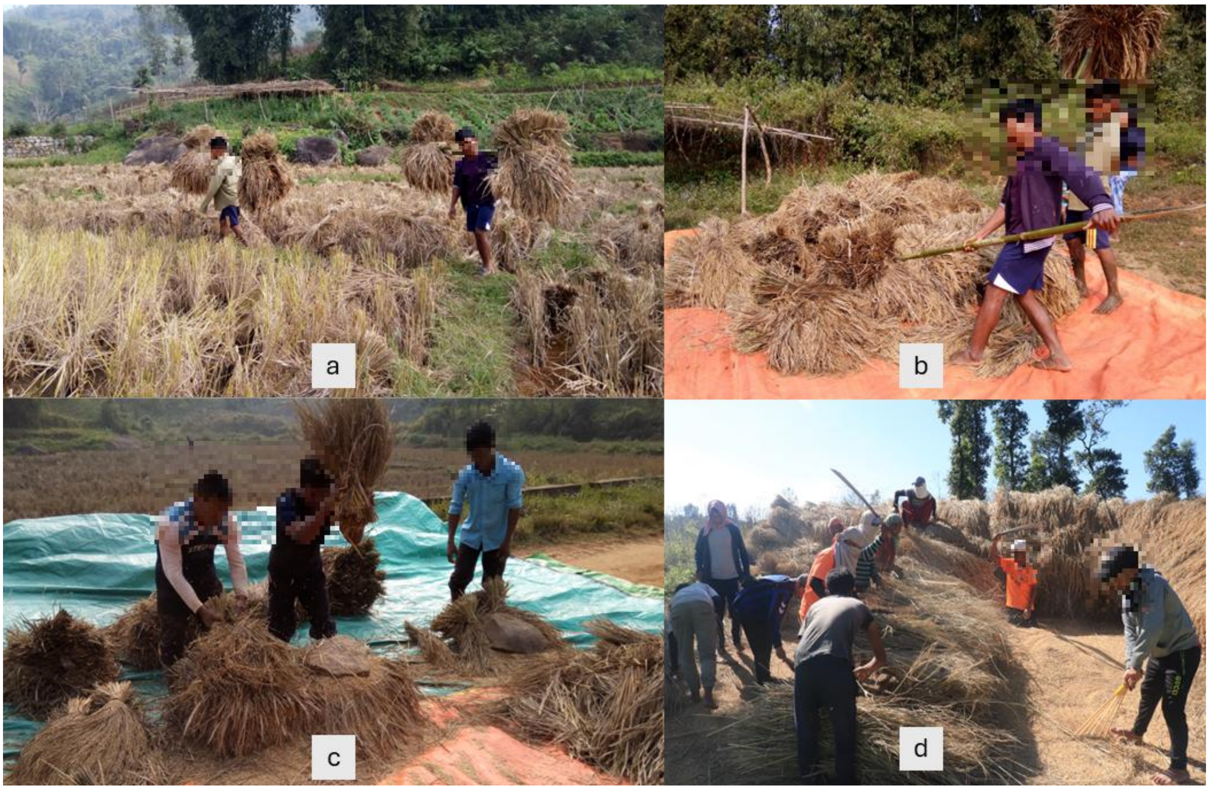

Figure 1. Prevalent Traditional Methods

Pedal Operated Thresher

Pedal-operated threshers provide intermediary mechanization such as lightweight, portable, and suitable for hilly or fragmented plots (Singh *et al.,* 2020). Capable of processing 40–60 kg/h, they decrease the labor burden by up to 60% and accelerate operation time by about 50% over manual techniques, all while being affordable for smallholders.

Ergonomic assessments in Meghalaya show that pedal threshers reduce physical strain and fatigue compared to traditional methods, improving working conditions without substantial economic risk (Singh H. J. *et al.,* 2024). Adoption rates, however, are contingent on local awareness and availability of improved designs (Goswami *et al.,* 2020).

Powered Paddy Thresher-Cum-Cleaner

Powered thresher-cum-cleaners integrating a threshing drum, blower, and sieving, deliver both labour and time savings. Fieldwork and government machinery reports show capacities of 140–150 kg/h, with labor savings reaching up to 65% (Singh *et al.,* 2022; Government of India, 2022). Belt and pulley covered machines improve operator safety and minimize post-harvest losses.

Comparative regional studies confirm that mechanized threshers produce cleaner output, reduce drudgery, and are favored where electricity can be sourced. Socio-economic surveys highlight their positive impact on rural labor productivity and gender equity, by freeing up time for other income-generating activities.

Tractor-Operated Thresher

Tractor-mounted threshers typically spike-tooth or axial-flow models offer bulk-processing capacities of 400–600 kg/h, reducing labor by 70–80% and operational windows by 60–70%. Their efficiency is particularly pronounced in accessible valley regions with available tractor infrastructure.

However, high upfront investment, fragmented holdings, and rugged terrain restrict their widespread adoption. Socio-economic analysis from Assam underscores the need for custom-hiring models and institutional credit to democratize access (Goswami *et al.,* 2020). Labour market research also finds mechanization impacts rural wage structures sometimes reducing demand for seasonal manual labour but creating new technical and operational opportunities.

Figure 2. Improved paddy threshing methods
(a. Manual thresher, b. Motorized thresher & c. Tractor operated thresher)

Comparison of Paddy Threshing Methods

Traditional paddy threshing techniques such as hand beating, animal trampling, and log beating require minimal initial investment but are highly labor-intensive. These methods yield relatively low productivity, typically between 10 and 74 kg per hour, and involve significant physical effort, increased grain damage, and overall low cost-efficiency (Ningthoujam *et al.,* 2020). Pedal operated threshers, priced between ₹20,000 and ₹30,000, enhance productivity to about 40–49 kg per hour while reducing physical strain. They halve operational costs compared to traditional methods and provide benefit-cost ratios near 2:1, indicating improved cost-efficiency (Ningthoujam *et al.,* 2020)

Powered paddy threshers powered by small engines elevate throughput substantially (up to ~223 kg/hr) and maintain relatively low operational costs (₹1550–₹1630 per ton). The integration of cleaning functions and moderate initial investments make these units economically viable, especially for farmer groups, with favorable payback periods. Tractor-operated threshers demand significantly higher capital but achieve very high capacity (1000–3000 kg/hr) and significantly reduce labor needs. Despite higher upfront costs, running costs remain competitive (₹1550–₹2744 per ton), making this method the most cost-efficient for large-scale farming.

Table 1. Comparison of paddy threshing methods

Method	Initial Investment	Operating Cost (per ton)	Machine Capacity (kg/hr)	Labour Required	Cost-Efficiency	References
Traditional Threshing	Negligible	₹3100–₹3500	30–74	High	Lowest (labour-intensive, high drudgery, low throughput)	Ningthoujam et al. (2020), Goswami et al. (2020), Lad et al. (2020), Rahaman et al. (2022)
Pedal Operated Thresher	₹20,000 – ₹30,000	₹1550–₹3100	40–49	Moderate	Improved (less labour, moderate cost)	Ningthoujam et al. (2020), Goswami et al. (2020), Lad et al. (2020), Rahaman et al. (2022)
Powered Paddy Thresher-cum-Cleaner	₹15,000 – ₹25,000	₹1550–₹1630	190–223	Low	High (low operating cost, high output, better cleaning)	Rahaman et al. (2022)
Tractor-Operated Thresher	> ₹2,00,000	₹1550–₹2744	1000–3000	Very Low	Very High (highest throughput, efficient labour use)	Weerasooriya e et al. (2011)

Determinants of Method Selection

Farmers' preferences for threshing techniques are shaped by:

- **Geography and landholding patterns:** Small, hilly plots favor portable devices or manual labor, while valley lands accommodate mechanized systems.
- **Economic and labour dynamics:** Rising harvest-time wages, acute labour shortages, and operational costs increasingly drive mechanization uptake.
- **Institutional support and ergonomic innovation:** Credit, subsidies, and extension services catalyze the adoption of safe and efficient threshing models (Government of India, 2022; Singh H. J. *et al.,* 2024).

Regional studies highlight that ergonomic design improvements can accelerate uptake by lowering fatigue and injury risk, especially among women and elderly farmworkers (Singh H. J. *et al.,* 2024).

Challenges and Opportunities for Sustainable Agriculture

The transition to mechanized and ergonomic threshing methods is both a challenge and opportunity for rural livelihoods. Indigenous practices remain ecologically adaptive yet are less scalable or productive as market pressures intensify. Mechanized adoption boosts productivity and labor efficiency but must be guided to mitigate negative local livelihood impacts.

Recent work suggests a balanced approach blending indigenous wisdom, ergonomic innovation, and mechanization tailored to farm size, terrain, and socio-economic circumstance optimizes outcomes for smallholder communities and supports sustainable agricultural growth (Ningthoujam *et al.,* 2020; Singh H. J. *et al.,* 2024).

Conclusions

Threshing practices in Northeast India must be approached holistically, factoring in cost, ergonomics, sustainability, and local context. Manual methods, while accessible, are increasingly constrained; semi-mechanized and advanced mechanized systems deliver significant labor and time savings, and when deployed via inclusive and ergonomic strategies, enhance farmer welfare. Cooperative models, targeted subsidies, and active extension services are critical for scalable and sustainable transformation.

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INNOVATIVE IPM COMBINING BIOCONTROL, BOTANICALS, AND DISEASE-RESISTANT VARIETIES

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Abstract

Integrated Pest Management (IPM) remains a cornerstone of sustainable agriculture, yet rising challenges such as pesticide resistance, environmental pollution, and risks to pollinators and human health highlight the need for innovative, holistic solutions. This article presents a synergistic IPM model that integrates biological control, botanicals, and pest- and disease-resistant crop varieties for ecologically sound pest regulation. Biological control through parasitoids, predators, and entomopathogens ensures long-term suppression of pest populations, while plant-derived pesticides, including neem-based formulations and other secondary metabolites, offer selective, rapidly degradable alternatives to conventional chemicals. Simultaneously, resistant cultivars developed via conventional breeding and modern molecular tools strengthen crop resilience and lower the frequency of chemical interventions. The combined use of these three components creates a complementary system that reduces chemical input, delays resistance development, preserves beneficial organisms, and supports climate-resilient agriculture. This article highlights the underlying mechanisms, case studies, practical considerations, and future opportunities, such as RNAi, CRISPR-based innovations, digital monitoring tools, and public-private collaborations, that can enhance adoption. The proposed integrative approach is scalable, economically viable, and suitable for both smallholder and commercial production systems, offering a pathway toward resilient and sustainable crop production.

Keywords: plant extract, microbial, disease, management, control, prevention

Introduction

Integrated Pest Management (IPM) is widely recognised as a cornerstone of sustainable agriculture, providing an ecologically balanced approach to reducing pest damage while minimising dependence on chemical pesticides (Angon *et al.*, 2023). Conventional IPM programs rely on a combination of cultural, mechanical, biological, and chemical tactics to keep pest populations below economic injury levels. Yet, the persistent challenges of pesticide resistance, environmental contamination, pollinator decline, and human health risks have underscored the need for more innovative, systems-based solutions. Advances in biological control, crop breeding, and plant-based pesticides have opened new avenues for redesigning IPM strategies that are both effective and environmentally sound.

Biological control, through the use of parasitoids, predators, and entomopathogens, plays a pivotal role in restoring natural pest regulation and can provide season-long suppression when carefully integrated. Botanical pesticides, including neem derivatives and other plant-based secondary metabolites, offer highly selective, biodegradable alternatives to synthetic chemicals, helping reduce ecological disruption and residue concerns. In parallel, the development of pest- and disease-resistant crop varieties, through conventional breeding and modern biotechnological tools, strengthens crop resilience and lowers the need for frequent interventions. Integrating these three components, biocontrol agents, botanicals, and resistant varieties, creates a synergistic IPM framework that enhances ecosystem services, protects biodiversity, and aligns with climate-smart agriculture goals.

This article examines the potential and practicality of such integrative strategies, discussing their modes of action, successful case studies, and relevance for sustainable crop production. Particular attention is given to their complementarity, economic viability, and scalability for both smallholder farmers and large-scale commercial systems.

Role of Biological Control

Biological control continues to be a cornerstone of ecologically sound pest management, offering a natural and sustainable means of regulating insect populations. Parasitoids, predators, and entomopathogens play vital roles in suppressing pest outbreaks and can be mass-reared and strategically released to enhance their effectiveness. For instance, *Trichogramma* species are widely deployed against lepidopteran pests, while predators such as *Chrysoperla carnea* provide broad-spectrum suppression of aphids, thrips, and whiteflies. Likewise, entomopathogenic fungi, including *Beauveria bassiana* and *Metarhizium anisopliae* have shown considerable promise for pest control in both open-field and protected cultivation systems. Incorporating biological control into IPM not only reduces dependence on synthetic pesticides but also slows the development of insecticide resistance and helps conserve agroecosystem biodiversity (Baker *et al.,* 2020).

Role of Botanicals

Botanical pesticides represent an environmentally friendly and farmer-acceptable alternative to conventional chemicals. Compounds such as azadirachtin from neem (*Azadirachta indica*), pyrethrins from chrysanthemum (*Chrysanthemum cinerariifolium*), and various essential oils disrupt insect feeding, development, and reproduction while exerting minimal impact on non-target organisms. Their rapid degradation in the environment minimises residue accumulation, making them particularly suitable for organic and residue-free farming systems. When used judiciously and at economic threshold levels, botanicals complement biological control by reducing pest pressure without adversely affecting parasitoids and predators, thereby maintaining the functional integrity of natural enemy complexes (Ayyangar and Nagasampagi, 1993).

Role of Resistant Varieties

Host plant resistance remains one of the most cost-effective and farmer-friendly components of IPM. Breeding efforts, ranging from conventional selection to marker-assisted breeding and modern biotechnological interventions, have led to the development of cultivars resistant to key insect pests and diseases. Resistance may be expressed through antixenosis (deterring insect colonisation), antibiosis (adversely affecting pest growth and reproduction), or tolerance (allowing the plant to withstand damage without significant yield loss). The use of resistant varieties decreases the frequency of chemical interventions, stabilises crop productivity, and provides a strong foundation for long-term pest management when integrated with biological control and botanicals (Khush and Chaudhary, 1981).

Synergistic Benefits of Integration

The strength of this approach lies in its capacity to exploit complementary mechanisms of action. Resistant varieties slow pest population buildup, providing natural enemies more time to act effectively, while botanicals can be applied in a targeted manner to suppress outbreaks without disrupting beneficial insect populations. This combination reduces selection pressure for pesticide resistance, delivers season-long protection, and promotes overall ecosystem stability. Beyond pest control, such integrated strategies improve soil health, safeguard pollinators, and enhance agroecosystem resilience under changing climatic conditions (Deguine *et al.,* 2021).

Implementation Challenges

Despite its clear advantages, the integrated use of biocontrol agents, botanicals, and resistant varieties demands careful design and field validation. Compatibility testing is essential to ensure that botanicals do not harm beneficial organisms or interfere with biological control. Farmers must have access to high-quality biocontrol products, authentic and standardised botanical formulations, and resistant seeds at affordable prices. Moreover, optimal timing, dosage, and site-specific recommendations are needed for effective implementation. Strengthening extension networks, promoting participatory research, and providing decision-support tools can facilitate farmer adoption and confidence in such integrated systems (Bueno *et al.,* 2021).

Future Prospects

Emerging technologies offer exciting prospects for advancing this integrative approach. RNA interference (RNAi), CRISPR-Cas–based genome editing, and microbiome manipulation can be harnessed to develop highly specific pest resistance and enhance natural enemy performance. Additionally, digital agriculture, through AI-driven pest forecasting, precision monitoring, and mobile-based advisory platforms, can optimise the timing and combination of interventions. Policy support, public–private partnerships, and incentive schemes for sustainable inputs will be crucial to scale up these approaches and encourage widespread adoption.

Conclusion

Combining biological control agents, botanicals, and resistant crop varieties represents a forward-looking and ecologically responsible model for pest management. This integrated strategy reduces pesticide dependence, protects beneficial organisms, and contributes to climate-resilient, sustainable food systems. Although challenges remain, particularly in terms of input availability, compatibility, and farmer outreach, the benefits far outweigh the limitations. Continued investment in research, technology transfer, and farmer capacity-building will be key to unlocking the full potential of this approach and ensuring its adoption across diverse agroecological zones.

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INTEGRATED FARMING SYSTEM: AN ECO - FRIENDLY APPROACH FOR SUSTAINABILITY

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Abstract
In Integrated Farming System, the linkage of three or four enterprises, the market shock on particular produce can be overcome with other two or three marketable produce linked in IFS. This will certainly help small and marginal category of farming community to overcome bad governance of the present set up. Integrated Farming System encountering different enterprise viz., Dairy poultry, goat rearing, fish farming , duck rearing, piggery, pigeon farming, rabbit rearing, apiary sericulture, mushroom culture, biogas, agri - horti, agro forestry, home stead garden etc., will certainly help the present day change in the food habit of the people also. At present, IFS is adopted at scattered level with their available resources and the farmer who adopt IFS necessity the benefit out of it. At least, with in another decade, 90% of the farming community will move towards the advanced technology. In this context, the government should help through banks and other financing sector to secure high cost enterprises to small and marginal category as their financial background is very poor. Apart from that, government should also make necessary arrangement to secure easily, the location specific enterprises indicated to the farmers at their nearest place.

Key words: Integrated Farming System, Sustainability, Eco-friendly

Integrated Farming System is a viable approach in which waste of one enterprise becomes the input of another thus making efficient use of resources. It helps in improving the soil health, weed and pest control, increase water use efficiency and maintains water quality. As this system minimizes the use of harmful chemical fertilizers, weed killers and pesticides and thus safeguards the environment from the adverse effects.

Integrated farming system are often less risky, if managed efficiently, they benefit from synergisms among enterprises, diversity produce environmental soundness (Lightfoot, 1990). Moreover, based on the principle of enhancing natural biological processes above and below the ground, the integrated system is the combination that reduces erosion, increases crop yields, soil biological activity and nutrient recycling, helps in efficient use of water, reduces pest and diseases, intensifies land use, improving profits and can therefore help reduce poverty and malnutrition and strengthen environmental sustainability. An integrated farming system consists of a range of resource-saving practices that aim to achieve acceptable profits and high and sustained production levels, while minimizing the negative effects of intensive farming and preserving the environment (Lal and Miller, 1990; Gupta *et al*., 2012).

All over the world, farmers work hard but do not make money, especially small farmers because there is very little left after they pay for all inputs (seeds, livestock breeds, fertilizers, pesticides, energy, feed, labour, etc.). The emergence of Integrated Farming Systems (IFS) has enabled us to develop a framework for an alternative development model to improve the feasibility of small sized farming operations in relation to larger ones. Integrated farming system (or integrated agriculture) is a commonly and broadly used word to explain a more integrated approach to farming as compared to monoculture approaches. It refers to agricultural systems that integrate livestock and crop production or integrate fish and livestock and may sometimes be known as Integrated Biosystems. In this system an inter-related set of enterprises used so that the “waste” from one component becomes an input for another part of the system, which reduces cost and improves production and/or income. IFS ensure that wastes from one form of agriculture become a resource for another form. Since it utilizes wastes as resources, we not only eliminate wastes but we also ensure overall increase in productivity for the whole agricultural systems. We avoid the environmental impacts caused by wastes from intensive activities such as pig farming.

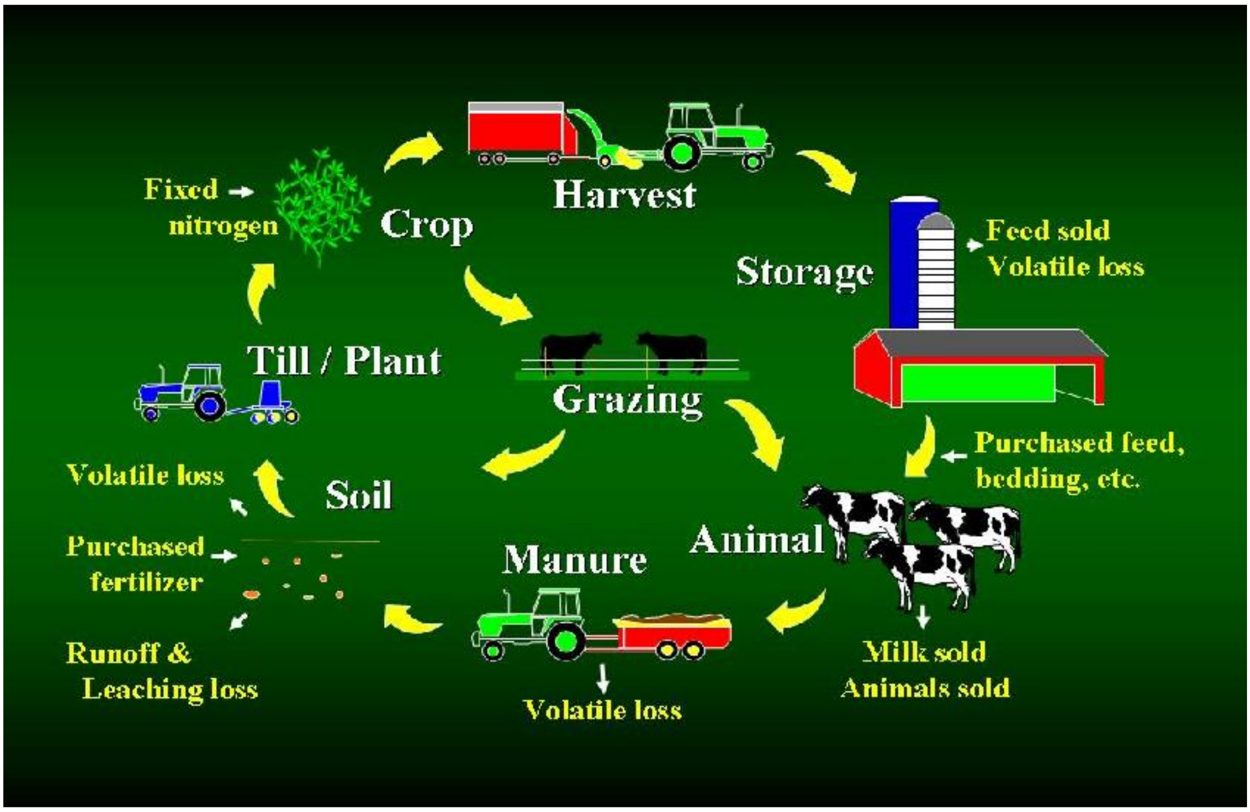

Fig. : Typical Integrated Farming System Model

Population of India is increasing by leaps and bounds. Cultivable land at the same time is limited and finite. In this context one has to consider the economic back ground of small and marginal category farmers who constitutes major chunk (82%) of the farming community of India. The challenge is to introduce such technological innovations to different regions of farm families in a manner that nullify the set back indicated. The concept of mixed cropping and Integrated Farming explained here under will enlighten the researcher to initiate projects accordingly. It is recent in origin evolved to overcome short falls, in mixed cropping practiced, until 1970’s. Farming system connotes a collection of land use systems and technologies in which different agri - oriented enterprises are deliberately linked on the same land with agricultural crops either in spatial arrangements or temporal sequences in an effort to optimize the use of accessible resources. Integrated Farming System (IFS) is relatively new word, not a new concept. The novelty lies in formally recognizing that enterprise mix posses contain common features that hold great promise in the tropics. Such system could improve productivity in quantity (through complimentary relationship) and qualitative (by using out puts that satisfy most producers needs, by enhancing net income) terms. None the less, they are also meant to be sustainable over time, in terms of both their ability to satisfy basic needs under present situation and to reduce system "Leakiness: by enhancing nutrient recycling and through recycling of no cost/low cost products of one enterprise over other. In the agricultural activity, prediction of stable income over years is not at all possible due to high fluctuation of marketable produces year to year. When there is glut in the market for a particular produce, the price of it reduces drastically and vice versa when it is deficit to market. Cost of cultivation in either case is same at the time of glut or deficit. The market fluction solely occurs on demand and supply of the particular producer. Because of the imperfect planning of the Government, it creates ravoc to the farmer.

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FROM BULK TO NANO: REDEFINING THE FUTURE OF FERTILIZERS

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Abstract

The transition from conventional bulk fertilizers to nanotechnology-based formulations represents a paradigm shift in plant nutrition. Conventional fertilizers, while instrumental in sustaining global food production, are often associated with nutrient losses, environmental pollution, and reduced nutrient-use efficiency (NUE). Nanofertilizers, designed at the nanoscale, offer controlled release, targeted delivery, and enhanced absorption by plants, thereby minimizing wastage and ecological damage. This paper critically examines the comparative advantages of nano-fertilizers over bulk chemical fertilizers, including their role in improving crop yields, soil health, and sustainability. Key agronomic evidence, mechanisms of nutrient release, and substitution ratios are highlighted to underscore their potential for reducing input costs, mitigating greenhouse gas emissions, and promoting climate-resilient agriculture. By integrating scientific insights with policy perspectives, this paper positions nano-fertilizers as a next-generation innovation capable of redefining the future of sustainable agricultural intensification.

Introduction

Agriculture in India is facing a wide spectrum of challenges in crop production system such as crop yield stagnation, declining organic matter, multi-nutrient deficiencies, climate change, shrinking arable land and water availability, resistance to GMOs, shortage of labour and finally enhancing crop productivity while promoting environmental sustainability. If Indian agriculture is to attain its broad national goal of sustainable agriculture growth of over 4%, it is important that the nanotechnology research is extended to the agricultural total production– consumption system, that is, across the entire agricultural value chain. This would require focusing on technologies that increase agricultural productivities, product quality and resource-use efficiencies that reduce on-farm costs, raise the value of production, and increase farm income; as well as on conserving and enhancing the quality of the natural resource base. It would also require a conscientious effort to provide a system to deliver these innovations based on nanotechnology to a product delivery stage and ensure that these reach the rural stakeholders at the end of the agri-value chain.

With the global population expected to surpass 9 billion by 2050, it is essential to enhance agricultural productivity while minimizing environmental impact. The increasing global population and consequent demand for food have made it essential to develop sustainable agricultural practices. Nanofertilizers are one such innovation that addresses this challenge by enhancing nutrient availability, uptake, and utilization in plants.

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Although traditional fertilizers play a key role in crop production, they often exhibit low nutrient utilization efficiency due to significant nutrient losses through leaching, volatilization, and fixation and contribute to problems such as soil degradation, water contamination, and greenhouse gas emissions. These losses decrease nutrient utilization and contribute to environmental challenges. Nanotechnology has emerged as a transformative solution in agriculture, with nano-fertilizers The introduction of nano-fertilizers in agriculture offers a potential solution to these challenges, playing a pivotal role. In agriculture sustainability. Indian Farmers Fertilizer Cooperative Limited, the world's largest Cooperative has taken a lead to the development of various Nanofertilizers formulations, including Nano-Urea Plus, Nano DAP, and two Nano micronutrient formulations - nano Zinc and Nano Copper (**Picture 1**).

Picture 1. IFFCO Nano-Urea Plus, Nano DAP, Nano Zinc and Nano Copper

These innovations have shown promising results in both controlled environments and field conditions. IFFCO Nanofertilizers demonstrate various advantages compared to traditional fertilizers, including increased efficiency due to the direct delivery of essential nutrients to plants and decreased environmental impacts through reduced required fertilizer amounts. This technology has the potential to not only maximize crop yields but also decrease the environmental effects of fertilizers.

Advantages of Nanofertilizers

Nano-fertilizers which are created using nanotechnology, are nutrient carriers with sizes ranging from 1 to 100 nanometres. The distinctive characteristics of nano-fertilizers, such as their nanoscale size, large surface area, and increased reactivity, render them significantly more efficient than traditional fertilizer options. Nanofertilizers provide several advantages over traditional fertilizers, which are listed below:

1. Greater Surface Area: The particle size of Nanofertilizers is less than 100 nm. which increases their capacity to penetrate plants from applied surfaces such as soil or leaves, boosting plant nutrient uptake, which supports a broader range of sites and diverse metabolic functions in plant systems, leading to more photosynthate production. The smaller particle size enhances the specific surface area and number of particles per unit area, enabling nano-fertilizers to interact more efficiently with nutrients. This improved interaction, which facilitates better nutrient penetration and absorption, ultimately increases nutrient utilization efficiency, which plays a crucial role in optimizing crop quality and overall productivity (Lairon,2010).

2. High Solubility: Nanofertilizers exhibit increased solubility due to their reduced particle size and larger surface area, which promotes dissolution in the soil solution. Nanofertilizers can dissolve easily in many solvents, such as water, resulting in the increased solubility of insoluble nutrients in the soil and enhanced availability of the nutrients to the organisms in the environment.

3. Encapsulation of Fertilizers within NPs: Due to the encapsulation of fertilizers in NPs, nutrient absorption in crops increases. The methods for encapsulating fertilizers include polymer-based encapsulation by forming a polymer matrix around the fertilizer through emulsion polymerization and interfacial polymerization. Another method is inorganic shell formation by incorporating inorganic materials, such as silica or calcium carbonate, which can form a shell around the fertilizer through sol-gel synthesis or precipitation (Vadlamudi et al. 2022). Yet another method is layer-by-layer assembly, which involves the sequential deposition of charged polymers, NPs, or other materials onto the fertilizer surface, forming a multi-layered shell. Nanofertilizers boost nutrient availability throughout crop development, reduce nutrient loss via denitrification, volatilization, and leaching, and fix nutrients in the soil, particularly NO_3 and NH_4 ions.

4. Easy Penetration and Controlled Release of Fertilizers: Nanofertilizers significantly aid the penetration of fertilizers into plant tissues, enhancing nutrient uptake and utilization by plants. The improved penetration is primarily attributed to the nano-sized particles that comprise Nanofertilizers, which possess a high surface area–to–volume ratio. These smaller particles can quickly diffuse through plant cell walls and membranes. Furthermore, the functionalization of these NPs with specific targeting molecules enables them to be selectively taken up by plant tissues, ensuring a precise delivery of essential nutrients. The improved penetration of Nanofertilizers reduces the amount of fertilizer required and minimizes nutrient leaching and runoff, thereby mitigating environmental pollution. Consequently, using Nanofertilizers for efficient penetration in plant tissues contributes to better crop yields, improved nutritional quality, and overall agricultural sustainability.

5. High Nutrient Absorption Efficiency: Nano-fertilizers are known to be more readily absorbed by the plant's surface due to their small size and high surface area, which allows for a better uptake of nutrients. Hence, when nano-fertilizers are foliar sprayed on plants during their vegetative stage, this can lead to robust growth, healthier foliage, and stronger stems, setting a solid foundation for the growth of the plant. The vegetative stage, which includes flowering, fruiting, and seed formation, is the most crucial stage for determining yield. Foliar application at this stage provides proper nutrition to plants, which can enhance flower formation, pollen viability, and pollination success and then increases the yield of the plant.

The foliar application of nutrients represents a targeted approach in which fertilizers are directly applied to plant leaves, enabling rapid absorption and translocation of nutrients throughout the plant system (Lovatt, 2013). This approach has attracted significant interest because of its capability to overcome limitations associated with soil-applied fertilizers, such as nutrient fixation, leaching losses, and poor soil conditions that may impede nutrient uptake. One example of this application method is the study on *Cucurbitta pepo* (*pumpkin*), where it was observed that the fertilizer was absorbed rapidly and there was an acceleration in the transition of elements when the fertilizers were foliar sprayed.

6. Effective Duration of Nutrient Release: The effective duration of nutrient release in Nanofertilizers has significant implications for agricultural productivity and sustainability. A key advantage of nano-fertilizers lies in their capacity to deliver nutrients in a controlled and precise manner, ensuring that all nutrients are aligned with crop requirements throughout the growing season, thereby improving utilization efficiency. It ensures that plants receive the necessary nutrients throughout the growth cycle. Moreover, the controlled release of nutrients minimizes nutrient losses, reducing the need for repeated fertilizer applications and mitigating environmental pollution. Their nanoscale properties offer superior effectiveness in plants, when compared with traditional fertilizers. Bulk fertilizers are only effective for a short time after application. However, Nanofertilizers may enhance the nutrition release duration.

7. Reduce Fertilizer Usage: Nanofertilizers increase fertilizer efficacy and the ratio of soil nutrient absorption in crop yield, hence decreasing fertilizer use by preventing volatilization, leaching and run-off of fertilizer nutrients. Foliar spraying of nano-fertilizers has been found to reduce fertilizer usage or even increase crop yields (Khardia et al. 2022). The study conducted by (Abd El-Azeim, et al 2020) to compare the effects of the foliar application of NPK nano-fertilizers to those of traditional chemical fertilizers, revealed that applying NPK nano-fertilizers at rates equal to or below the recommended levels for conventional NPK fertilizers had a positive impact on biological yield, economic yield, and the fresh and dry weights of tubers and vegetative parts of potatoes. The foliar application of NPK nano-fertilizers on the potatoes was noted to increase plant vegetative growth and leaf area, which enhanced the utilization of solar radiation essential for the photosynthesis process and chlorophyll formation. This led to the vigorous growth of the potato, hence the increased fresh and dry weight noted after the experiment. Foliar spraying, in particular, significantly enhanced potato production, improving both yield and quality for both nano- and conventional fertilizers. Remarkably, under field conditions, the foliar application of NPK nano-fertilizers at 25% or 50% of the recommended rate was found to be equally or even more effective than applying 100% of conventional NPK fertilizers in improving potato yield-associated parameters. Furthermore, the slow release of nutrients provided by Nanofertilizers reduces the need for frequent applications and labour costs. As nanotechnology continues to improve, these fertilizers will become even more efficient and cost-effective, allowing farmers to produce more with less.

8. Improved Microbial Activity: The interaction between NPs and microorganisms, the shelf life of biofertilizers, and the dissemination of Nanofertilizers are among the most crucial variables in plant growth. Nano biofertilizers combine NPs and living microorganisms designed to improve plant growth and yield by enhancing nutrient uptake and soil fertility. It improves the structure and function of soil and the morphological, physiological, biochemical, and yield attributes of plants. The formation and application of nanofertilizers are a practical step toward smart fertilizer that enhances growth and augments the yield of crops.

9. Improved Soil Activity: Soil activity is a measure of the biological activity in the soil, including decomposition and nutrient cycling. These processes are essential for maintaining healthy soil and are driven by soil microorganisms, such as bacteria and fungi. Nanofertilizers increase soil activity by providing efficient delivery of nutrients to the root zone. Nanofertilizers increase the activity of soil microorganisms, leading to improved decomposition of organic material and increased nutrient cycling. Nanofertilizers increase the nitrogen mineralization rate in soil, a crucial process for maintaining soil fertility. They improve the activity of soil bacteria and fungi, essential for maintaining the soil ecosystem. Nanofertilizers can help maintain the soil pH balance, positively affecting plant growth.

10. Improved Soil Water-Holding Capacity: Nanofertilizers improve soil structure and water-holding capacity, increase organic matter, and create favourable conditions for beneficial microorganisms. They also contain humic acid and clay, which bind soil particles and reduce water loss through runoff and evaporation, resulting in better crop yields and improved soil health. Moreover, some Nanofertilizers, particularly those based on clay and carbon NPs, can bind soil particles together, forming larger aggregates. The improved soil aggregation leads to better soil structure, enhancing water-holding capacity and reducing soil erosion.

11. Eco-friendly Nature: Besides being more efficient, Nanofertilizers are much safer for the environment. Traditional fertilizers release large amounts of nitrogen and phosphorus into the soil, which can cause eutrophication and algal blooms in nearby water bodies. Nanofertilizers, on the other hand, are designed to release their nutrients slowly over time, allowing for more nuanced control of the nutrient balance in the soil and reducing the risk of environmental damage from nutrient runoff. Since they are more efficient than traditional fertilizers, they require less input, meaning farmers can save money on fertilizer costs. Nanofertilizers reduce the amount of fertilizer runoff, which can harm the environment. All these factors help in stimulating plant growth.

12. Low Production Cost: Nanofertilizers could attain lower production costs due to enhanced nutrient use efficiency, controlled release, and targeted delivery, reducing the wastage of fertilizers in the field. Nanofertilizers are typically much cheaper than conventional fertilizers as they are less labour-intensive, need lower fertilizer per application, and have higher absorption rates than traditional fertilizers. Furthermore, Nanofertilizers can remain in the soil for extended periods, resulting in fewer applications and lower costs.

13. Fulfils the Goal of Precision Farming: Precision farming is an agricultural production management system that uses information technology to measure and manage crop production inputs such as fertilizers, pesticides, and water. Recent advances in nanotechnology have allowed Nanofertilizers to develop, which may be used to improve precision farming practices. The use of Nanofertilizers for precision farming offers several potential benefits. Firstly, Nanofertilizers can be directly applied to the plant, enabling a more precise application than traditional fertilizers. This results in reduced costs, lower fertilizer input, and a lesser runoff volume that may enter the environment. In addition, Nanofertilizers can deliver specific nutrients to the plant, allowing for more precise crop nutrition management. Finally, Nanofertilizers can also provide other substances in the plant, such as micronutrients and growth regulators.

14. Improves Plant Stress Tolerance: Plants are affected by numerous environmental stresses throughout their life cycle. As a result, they modify genetic, biochemical, and physiological pathways to strengthen their defence against environmental stresses in various phases. Plants respond to such types of abiotic stress by altering gene expression at the molecular level. Multiple studies show that NPs' impact on plant growth and development is dose-dependent. In plants, the signalling system excites the defence machinery, which activates molecular mechanisms to respond to diverse stress circumstances. Nanofertilizers have been found to improve plant stress tolerance in several ways.

The nanoscale particles of the fertilizers can penetrate the cell walls of plants, allowing nutrients to reach the root system and other parts of the plant more quickly. In addition, Nanofertilizers may also help plants better tolerate environmental stressors, such as drought or extreme temperatures. For example, Nanofertilizers can provide essential nutrients that help plants remain healthy despite water shortages or heat waves. Moreover, Nanofertilizers can also offer beneficial protective compounds, such as antioxidants, that can help plants cope with environmental stressors.

15. Stimulates Plant Growth: NPs increase the availability of essential nutrients such as nitrogen, phosphorus, and potassium, which are necessary for the growth and development of plants. NPs also assist in the uptake of these essential nutrients, allowing plants to utilize them more efficiently. Application of Nano-fertilizers at a concentration of 5 mL/L, administered twice as a foliar spray during the vegetative growth stage, demonstrated a superior ability to enhance the height of coriander, which led to more branching and a full umbrella capacity due to the presence of essential nutrients and improved use of environmental factors, resulting in a higher yield (Nejatzadeh, 2024). The timing and frequency of foliar applications also play crucial roles in determining their effectiveness. Research has demonstrated that the timing of application is crucial for optimizing nutrient uptake and efficiency (Janmohammadi, et al. 2016). Applying nano-fertilizers via foliar spraying during the vegetative and reproductive stages significantly improved yield characteristics and overall crop performance (Verma, et al. 2024).

Apparently, Nano-fertilizers excel in controlled and precise nutrient release compared to traditional bulk fertilizers. Various advantages of Nanofertilizers are Displayed in Figure 1.

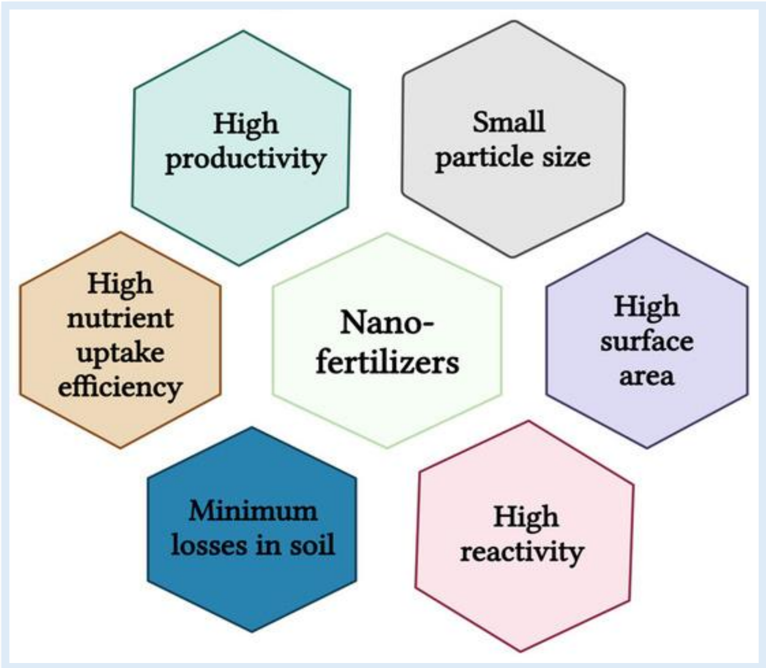

Figure 1. Advantages of nano-fertilizers
Source: Seleiman et al. (2020)

Impact on Crop Yield and Quality

Field and greenhouse experiments have demonstrated that using different nano-fertilizers can improve yields. Specifically, applying NPK nano-fertilizers has been effective in balancing rice yield and quality while improving fertilizer efficiency (Sadati, et al.2021). (Kumar and Dahiya, 2024) stated that during tillering stages, the foliar spraying of nano-nitrogen and nano-copper fertilizers led to increased grain and straw yields in wheat. Additionally, nano-fertilizers enhance nutrient bioavailability, stimulate various plant pathways and enzymes, boost root biomass, and boost the microbial population in the rhizosphere, which are key factors for optimizing crop productivity. In a greenhouse experiment, (Ghahremani et al. 2014) investigated the effects of varying concentrations of nano-calcium and nano-potassium chelate fertilizers on the quantity and quality traits of basil. It was effective in improving the 1000-seed weight, harvest index, grain yield, and biological yield compared to the control and other treatments. (Asadzade et al. 2015) investigated the impact of traditional fertilizers and nano-fertilizers (ZnO and SiO_2) on sunflower yield and harvest index. The study found that ZnO nano-fertilizer significantly enhanced parameters such as head diameter, seed yield, 1000-seed weight, and the number of seeds per head compared to the control plot and other treatments. (Manikandan and Subramanian, 2016) carried out two greenhouse experiments utilizing soils with different textures—Inceptisols and Alfisols—to assess the growth-promoting effect of zeolite-based nitrogen nano-fertilizers in comparison to conventional fertilizers. The findings revealed that maize grain yield was significantly greater with the nano-zeolite treatment than with the conventional urea treatment used as the control. Abd EL-Azeim et al. (2020) conducted a study to evaluate the effects of soil-applied NPK nano-fertilizers and chemical fertilizers on potato crop yield and its parameters. After the investigation, it was found that foliar application significantly influenced the effectiveness of both nano- and conventional fertilizers on potato production and yield quality compared to soil application. All treatments involving nano- or chemical fertilizers improved potato yield parameters, including the fresh and dry weights of tubers, relative to the control. These findings suggested that prioritizing the use of nano-fertilizers was advisable, but at equal or lower application rates, to achieve optimal potato yield.

In sustainable agriculture, nano-fertilizers can be used for more than yield enhancement. As advanced fertilizers, they are expected to increase nutrient utilization, decrease environmental pollution, and improve crop quality (Rehim, et al. 2021). The responsive behaviour of nano-fertilizers has established their potential to reduce the total fertilizer requirement without compromising or even increasing crop productivity (Piao, et al. 2022). The development of crop-specific fertilizer management strategies has gained increasing attention. Different crops exhibit varying nutrient requirements and absorption patterns, necessitating tailored approaches to fertilizer application (Kumalasari, et al. 2022) Understanding these specific needs helps in developing more efficient and sustainable fertilization practices. Combining nano-fertilizers with traditional fertilization programs has shown promising outcomes across various crops. An example is the study on maize, which revealed that the foliar application of nano-NPK fertilizer, alongside reduced amounts of conventional fertilizers, improved the growth of maize, yield components (ear grain weight, cob weight, 500-grain weight, and number of grains per ear), and nutrient utilization (Zaki and Ahmed, 2023). Positive results like these have also been observed in rice (Chandana et al. 2021) and wheat cultivation systems. Al-Juthery et al. (2018) in their study focused on the application of various nano-fertilizer treatments through foliar spraying on wheat. It was identified that foliar application of nano-fertilizers facilitates rapid absorption, enhancing fertilizer efficiency, crop growth, and nutrient uptake.

IFFCO's Action Plan to Promote Nano Fertilisers

IFFCO's action plan to promote Nano fertilisers for climate-resilient agriculture involves a multi-faceted approach. Firstly, a nationwide “Nano Fertilizer Usage Promotion Mahaabhiyan” has been launched, establishing 200 model nano village clusters across 800 villages. In these clusters, farmers receive a 25% subsidy on Nano Urea Plus and Nano DAP fertilizers to encourage widespread adoption. To modernize and make application affordable, IFFCO grants drone entrepreneurs Rs100 per acre, supporting low-cost, precision spraying services in the field. Awareness campaigns, publicity drives, and extensive field demonstrations are conducted to illustrate the yield and quality benefits of nano fertiliser adoption. Training programs for cooperative society secretaries and collaborations with the Ministry of Fertilisers aim to build local capacity and ensure availability at all *Pradhan Mantri Kisan Samridhi Kendras* (PMKSK).

A 100-day government action plan complements these initiatives, targeting 1,270 demonstrations of Nano DAP and 200 trials of Nano Urea Plus in selected districts nationwide, in collaboration with research institutions and *Krishi Vigyan Kendras*. The strategic rollout includes the distribution of 6 crore bottles of nano fertilisers via IFFCO's 36,000-member cooperative societies, ensuring robust supply chains even in remote areas. IFFCO also prioritizes continuous monitoring, feedback collection, and adjustments based on field results to sustain efficacy and safety standards.

This comprehensive promotion and action plan aims not only to reduce India's dependency on chemical fertilisers, but also to build farmer resilience against climate variability, conserve soil and water resources, enhance farm incomes, and foster large-scale adoption of clean agricultural technologies for a greener and more secure future (**Picture 1**).

Picture 1. Model On- Farm demonstrations for farmers education

A model for on-farm demonstrations for farmer education involves setting up practical, field-based learning environments where farmers can observe, engage, and implement improved agricultural practices. These models are structured to maximize hands-on experience and knowledge exchange. The success of these models depends on localized tailoring—considering the ecosystem, crops, soil, climate, and cultural aspects of each community for maximum relevance and adoption. On-farm demonstrations are typically organized by agricultural universities, industry,s extension services, NGOs, or farmer organizations, and serve both educational and research goals. A few examples of On-farm demonstration conducted by IFFCO field executives are depicted in Pictures 2.

Picture 2. A view of IFFCO's Nano Urea Plus & Nano DAP On-Farm Trials

In conclusion, promoting fertilizer use efficiency through smart fertilizer marketing is a win-win for farmers, the environment, and national food security. By adopting a multi-pronged approach that combines innovation, education, digitalization, and policy support, India can transform its fertilizer use paradigm toward precision, profitability, and sustainability.

Benefits of application of Nano fertilisers through Drone

The application of IFFCO Nanofertilizers through drones offers significant benefits for Indian agriculture, enhancing efficiency, reducing costs, protecting the environment, and improving farmer safety. Up to 90% of nutrients in nano fertilizers applied via drones are absorbed by plants, minimizing runoff and reducing pollution of air and water. The targeted and uniform distribution means less fertilizer is needed, cutting down on overall input cost for farmers. Drones can spray large areas very quickly—up to 2.5 acres in 15 minutes—drastically cutting the time needed for application compared to manual methods. Field trials have demonstrated stronger and healthier crops, eliminates direct farmer exposure to fertilizers and agrochemicals, lowering health risks. Nano fertilizers like IFFCO Nano Urea have minimal environmental impact, reducing greenhouse gas emissions and improving air and water quality due to precise, foliar application and lower chemical load. As drone services become increasingly available (e.g., through IFFCO's rural entrepreneur training), even smallholders can afford professional spraying.

Future Outlook

The future of nano urea and Nano DAP in India appears promising, with potential to reduce conventional urea and DAP dependence by 20–30% in the next decade. If integrated with climate-smart practices, Nano Urea Plus and Nano DAP can play a significant role in reducing the environmental footprint of Indian agriculture while enhancing farmers' income. The development of other nano-based fertilizers such as IFFCO Nano Zn and Nano Cu further indicates a broader transformation in plant nutrition management. Nevertheless, success will depend on continuous R&D, farmer-friendly extension services, and adaptive policy mechanisms that address both economic and ecological concerns.

Conclusion

Nano urea and Nano DAP represent a paradigm shift in Indian fertilizer management by offering a sustainable and efficient alternative to conventional urea and DAP. Their benefits in reducing nitrogen losses and phosphorus fixation saving subsidy costs, and supporting environmental sustainability are substantial. However, realizing its full potential requires robust field validation, farmer education, regulatory safeguards, and integration within balanced nutrient management systems. As India moves toward self-sufficiency in urea and DAP, nano urea and Nano DAP will likely occupy a central role in shaping the future of Indian agriculture.

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MICROGREENS: NUTRIENT-DENSE FUNCTIONAL FOODS FOR SUSTAINABLE HEALTH AND FOOD SECURITY

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Abstract
Microgreens are the young seedlings of vegetables and herbs harvested 7–21 days post-germination, have emerged as nutrient-dense functional foods with significant health-promoting potential. Characterized by vibrant colours, intense flavours, and elevated concentrations of vitamins, minerals, antioxidants, and bioactive compounds, they offer a promising approach to mitigating micronutrient deficiencies and enhancing dietary diversity. This review provides a comprehensive overview of microgreens' definition, classification, nutrient profile, and associated health benefits, including cardiovascular protection, anti-inflammatory effects, glycaemic regulation, and neuroprotection. Advances in cultivation techniques such as hydroponics, vertical farming, and controlled environment agriculture have improved yield, nutritional quality, and sustainability, supporting their role in addressing food security challenges. Additionally, the article explores value-added applications, market potential, and emerging consumer trends, highlighting opportunities for innovation in functional foods. Despite challenges related to limited shelf life, consumer awareness, and the need for more in vivo validation, microgreens present a viable strategy for promoting sustainable nutrition, particularly in urban and resource-limited settings.

Key words: Microgreens, Functional foods, Bioactive compounds, Sustainable agriculture, Food security.

Introduction

Microgreens are the young seedlings of vegetables and herbs which have emerged as a promising category of functional foods due to their high nutrient density and potential health benefits. These small, tender plants are typically harvested 7-21 days after germination and are renowned for their vibrant colours, intense flavours, and rich nutritional profiles. As interest in sustainable and health-promoting foods grows, microgreens are gaining attention for their role in addressing nutritional deficiencies and enhancing dietary diversity. This article examines various aspects of microgreens, including their definition and classification, cultivation techniques, health benefits, and market potential.

Research on microgreens has emerged as a critical area of inquiry due to their potential to address nutritional security and promote sustainable food systems amid global population growth and urbanization (Dubey *et al.,* 2024) (Dhaka *et al.,* 2023). Initially gaining attention in the 1980s as culinary garnishes, microgreens have evolved into recognized functional foods rich in vitamins, minerals, and bioactive compounds (Charlebois, 2018). Their short growth cycle, minimal resource requirements, and adaptability to controlled environments position them as promising crops for urban agriculture and vertical farming (Teng *et al.,* 2022) (Budavári *et al.,* 2024). The global microgreens market is expanding rapidly, projected to grow from 1.7 billionin 2022 to1.7 billion in 2022 to 1.7 billionin 2022 to 2.61 billion by 2029, reflecting increasing consumer demand driven by health awareness and environmental concerns (Singh *et al.,* 2024) (Das, 2024).

Despite growing interest, challenges remain in fully understanding microgreens' nutritional profiles, cultivation techniques, and market potential (Wheeler, 2023) (Lone *et al.,* 2024). Although numerous studies report elevated levels of antioxidants, vitamins, and minerals compared to mature plants, comprehensive assessments of their overall nutritional rating and bioavailability are limited (Tallei *et al.,* 2023) (Johnson *et al.,* 2021) (Pant *et al.,* 2023). Moreover, variations in species, growing media, light conditions, and postharvest treatments contribute to inconsistent quality and shelf life, complicating commercialization (Balik *et al.*, 2024) (Patil *et al.,* 2024) (Sinchana *et al.,*2024). Controversies also exist regarding microbial safety risks, especially compared to sprouts, and the environmental sustainability of commonly used peat-based substrates (Wheeler, 2023) (Poudel *et al.,* 2023). These gaps hinder the optimization of production systems and consumer acceptance, restricting microgreens' broader adoption as functional foods (Krishnan *et al.,* 2024) (Das, 2024).

Basically, microgreens are defined as young seedlings harvested at the cotyledon or first true leaf stage, characterized by concentrated nutrient density and distinct sensory attributes (Kyriacou *et al.,* 2016) (Seth *et al.,* 2025). Their classification spans diverse botanical families, with nutritional and phytochemical profiles influenced by genotype and cultivation conditions (Amil *et al.,* 2024) (Pant *et al.,* 2023). The interplay between cultivation techniques, nutrient biofortification, and postharvest management shapes their health benefits and market viability (D'Imperio *et al.,* 2023) (Kathi *et al.,* 2023). This framework underpins the systematic evaluation of microgreens as sustainable functional foods with potential to mitigate micronutrient deficiencies and chronic diseases (Sobhanan & Meena, 2024) (Gupta *et al.,* 2023).

Definition and Classification

Microgreens are defined as young, edible seedlings of vegetables and herbs, harvested at an early stage of growth, typically 7-21 days after germination (Seth *et al.,* 2025) (Sobhanan & Meena, 2024). Microgreens can be classified into various categories based on their species, including common examples such as basil, cilantro, and broccoli, each offering unique flavours and nutritional benefits. Microgreens not only provide essential nutrients but also contribute to the prevention of chronic diseases, making them a valuable addition to modern diets (Bhaswant *et al.,* 2023). Their vibrant colours and flavours enhance culinary experiences while promoting health awareness among consumers (Işik *et al.,* 2022).

They consist of a central stem, cotyledons and the first true leaves, and are distinct from sprouts and mature plants due to their higher concentration of nutrients (Seth *et al.,* 2025) (Krishnan *et al.,* 2024). Microgreens serve as a bridge between nutrition and culinary art, offering not only essential vitamins and minerals but also unique flavours that can transform dishes into healthful gourmet experiences. Moreover, the integration of microgreens into everyday meals can significantly improve dietary variety and nutritional quality, making them an excellent choice for health-conscious consumers.

Common types of microgreens include those from the Brassicaceae family, such as broccoli and kale, which are noted for their bioactive compounds like glucosinolates (Alloggia *et al.,* 2023). Incorporating microgreens into daily diets can not only enhance flavour and aesthetics but also provide essential nutrients that combat malnutrition and support overall health (Bhaswant *et al.,* 2023; Seth *et al.,* 2025).

Nutrient Profile and Health Benefits

Microgreens are rich in vitamins (C, E, K), minerals (iron, magnesium), antioxidants (glucosinolates, carotenoids, phenolic compounds), and other nutrients like fibre and omega-3 fatty acids (Tallei *et al.,* 2023) (Sobhanan & Meena, 2024). Their potential to address micronutrient deficiencies, particularly in vulnerable populations, underscores the importance of integrating microgreens into health-promoting dietary strategies (Seth *et al.,* 2025).

They have been shown to promote cardiovascular health, reduce inflammation, combat cancer, manage diabetes and protect the nervous system (Tallei *et al.,* 2023) (Krishnan *et al.,* 2024). Furthermore, the incorporation of microgreens into meals can enhance overall dietary quality and contribute to the prevention of non-communicable diseases, aligning with current health trends and nutritional needs (Bhaswant *et al*., 2023) (Seth *et al*., 2025).

Owing to their high nutrient density, they can play a pivotal role in mitigating micronutrient deficiencies, particularly among populations with restricted access to diverse and nutrient-rich diets. This potential is especially significant in regions where malnutrition is prevalent, making microgreens a key component in addressing dietary inadequacies and promoting health (Seth *et al*., 2025).

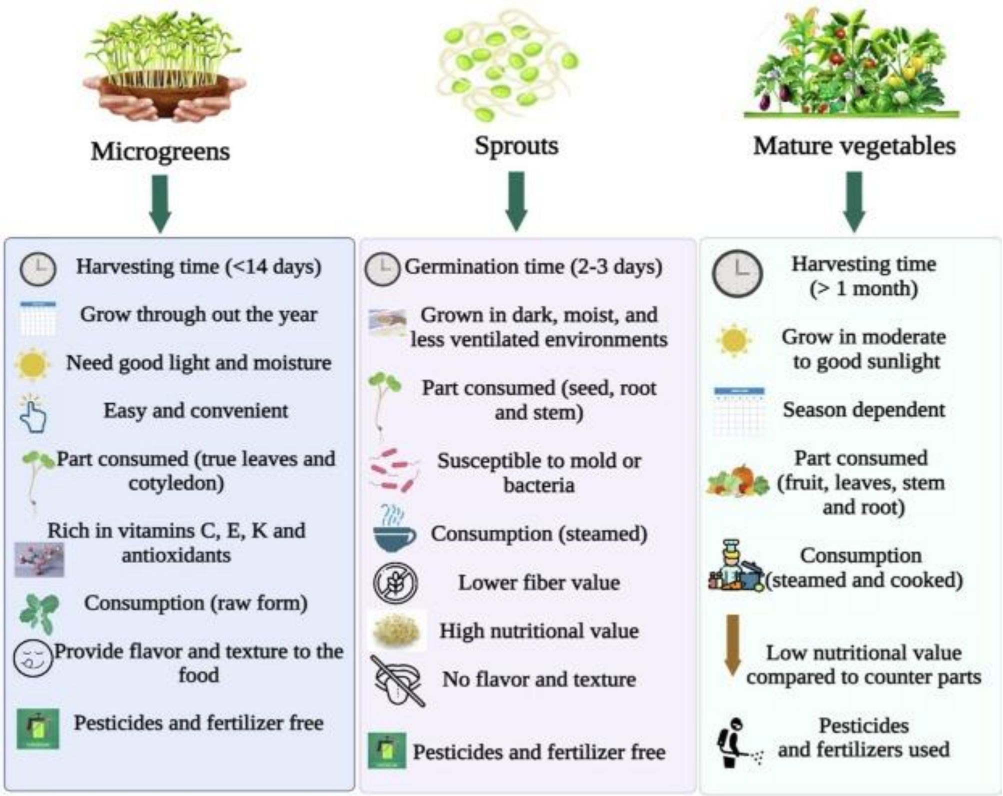

Fig. 1. Characteristics and properties of microgreen, spouts and matured vegetables. Source: (Partap *et al*.)

Cultivation Techniques

Microgreens can be cultivated in various systems, from simple home gardens to sophisticated vertical farms with automated controls for irrigation, lighting, and fertilization (Teng *et al*., 2022). Innovative growing methods, such as hydroponics and controlled environment agriculture, enhance the efficiency and yield of microgreens while ensuring optimal nutrient retention and growth conditions. (Zhang *et al*., 2021). These techniques not only maximize the use of space but also contribute to sustainable food production practices, making microgreens accessible to a broader audience.

Factors such as substrate, seed density, and growing conditions significantly influence the nutritional quality and yield of microgreens (Seth *et al*., 2025) (Alloggia *et al*., 2023). Implementing integrated multiomics approaches can further improve microgreens' nutritional profiles and growth traits, enhancing their role in sustainable agriculture and food security (Gupta *et al*., 2023). The integration of microgreens into sustainable agricultural practices can significantly contribute to enhancing food security and addressing nutritional deficiencies on a global scale (Gupta *et al*., 2023) (Seth *et al*., 2025).

Innovative cultivation methods, including the use of artificial lighting and optimized fertilization, can enhance the concentration of bioactive compounds in microgreens (Alloggia *et al*., 2023). These advancements not only improve the nutritional value of microgreens but also support their viability as a sustainable food source in various environments. The continued research into microgreens' cultivation and nutritional benefits is essential for developing effective strategies to combat malnutrition and promote health across diverse populations (Seth *et al*.,2025). Additionally, promoting the consumption of microgreens can empower communities to address their nutritional needs and foster sustainable agricultural practices that enhance food security and health outcomes.

Value-Added Applications and Market Potential

Microgreens are increasingly used in culinary applications for their distinct Flavors and aesthetic appeal, making them popular in upscale dining and premium grocery outlets (Singh *et al*., 2024) (Krishnan *et al*., 2024). The growing interest in microgreens presents opportunities for entrepreneurs and farmers alike to tap into this lucrative market, fostering innovation in sustainable agricultural practices. As the demand for nutritious and visually appealing foods rises, microgreens are positioned to play a significant role in enhancing culinary experiences while promoting health and sustainability in agriculture.

The global market for microgreens is projected to grow significantly, driven by consumer interest in health benefits and sustainable food sources (Singh *et al*., 2024). This growth reflects a broader trend towards functional foods that not only satisfy culinary desires but also contribute to improved health outcomes and sustainable practices in food production.

Value-added products, such as microgreen-based supplements and processed foods, offer opportunities for market expansion and diversification (Seth *et al*., 2025). The potential for microgreens to enhance food variety and nutritional value is particularly relevant in regions facing significant malnutrition challenges, highlighting their role in sustainable agriculture and health promotion (Seth *et al*., 2025).

Study Reference	Nutrient Profile Analysis	Cultivation Technique Efficiency	Health Benefit Validation	Market Potential Assessment	Sustainability Indicators
(Teng *et al.*, 2022)	Rich in phytonutrients, vitamins, and minerals with space farming potential	Diverse systems from home gardens to vertical farms with automation	Limited in vivo data; potential for crew health in space	Emerging market with growth potential but technical challenges	Low resource use, suitable for controlled environments
(Kyriacou *et al.*, 2016)	Species-specific biofortification and antioxidant enhancement	Preharvest factors like lighting, fertilization, and packaging affect quality	Antimicrobial and antioxidant properties noted; shelf-life extension needed	Market growth linked to quality and shelf-life improvements	Emphasis on non-chemical treatments and sustainable packaging
(Nethra *et al.*, 2024)	Nutrient-rich microgreens with culinary applications	Focus on urban agriculture and controlled environment farming	Health benefits highlighted, but more clinical data needed	Urban food systems integration supports market growth	Sustainable urban food production emphasized
(Dubey *et al.*, 2024)	Nutrient profile tailored by environmental and cultural factors	Controlled Environment Agriculture (CEA) enhances yield and quality	Functional food properties with nutraceutical benefits	Increasing variety and demand in indoor farming	CEA reduces environmental footprint, promotes sustainability
(Lone *et al.*, 2024)	Elevated nutrients and bioactive compounds confirmed	Various cultivation methods including germination biochemistry	Validated antioxidant, anticancer, anti-inflammatory effects	Commercial significance growing, especially in climate-vulnerable areas	Sustainable food production potential in arid regions
(Rebolledo *et al.*, 2024)	High nutritional quality consistent across seasons	Unheated greenhouse cultivation effective for diverse species	Sensory acceptance supports health benefit claims	Positive consumer acceptance and regional market opportunity	Low energy input cultivation with local adaptation
(Singh *et al.*, 2024)	High phytochemical content and intense flavors	Modern agricultural methods maximize growth	Consumer perception linked to health benefits	Market predicted to grow from 1.7Bto1.7B to 1.7Bto2.61B by 2029	Income disparities and awareness affect market expansion

Study Reference	Nutrient Profile Analysis	Cultivation Technique Efficiency	Health Benefit Validation	Market Potential Assessment	Sustainability Indicators
(Dereje *et al.*, 2023)	Rich in phytochemicals with antioxidant, anticancer properties	Growing practices and postharvest tech influence quality	Health benefits well documented in Brassicaceae microgreens	Novel food product development underway	Year-round production with minimal inputs supports sustainability
(Amil *et al.*, 2024)	Phytochemical diversity across botanical families	Various cultivation methods in Southeast Asia	Antioxidant and antimicrobial activities validated	Emerging market in Southeast Asia with growing interest	Urban cultivation supports sustainable agriculture
(Tallei *et al.*, 2023)	Abundant antioxidants and vitamins quantified	Species and growing conditions affect antioxidant content	Cardiovascular, anti-inflammatory, anticancer benefits	Commercial potential highlighted with research gaps	Functional food and nutraceutical applications explored
(Krishnan *et al.*, 2024)	Higher nutritive compounds than mature plants	Packaging and pre/post-harvest interventions affect shelf-life	Anti-cancer, anti-inflammatory properties noted	Culinary popularity increasing	Need for more in vivo and clinical trials
(Pant *et al.*, 2023)	Comprehensive biochemical and mineral profiling	Metabolite profiling reveals health-beneficial fatty acids	Antioxidant and nutritional potential established	Functional food potential to address micronutrient deficiencies	Supports overcoming hidden hunger sustainably
(Marta *et al.*, 2024)	Antioxidant content influenced by substrate and biostimulators	Hemp substrate enhances antioxidant compounds	Antioxidant activity measured by multiple assays	Potential for functional food applications	Organic biostimulators compatible with sustainable cultivation

Challenges and Future Prospects

Despite their benefits, microgreens face challenges such as limited shelf life and the need for improved consumer awareness and education (Sobhanan & Meena, 2024) (Singh *et al.*, 2024). To overcome these challenges, strategies focused on enhancing storage methods and educating consumers about the nutritional advantages of microgreens are essential for market growth and sustainability. Research on microgreens is still in its early stages, necessitating further exploration of their health benefits and potential applications in various sectors to fully realize their impact on nutrition and food security.

Research into extending shelf life and maintaining nutritional quality post-harvest is crucial for commercial viability (Sobhanan & Meena, 2024). Implementing innovative postharvest technologies can significantly enhance the shelf life and nutritional quality of microgreens, ensuring they remain a viable option for consumers seeking healthful foods.

As functional foods, microgreens hold potential for addressing malnutrition and promoting sustainable agriculture, particularly in urban and resource-limited settings (Nethra *et al.*, 2024) (Sobhanan & Meena, 2024). Microgreens can play a pivotal role in improving food security and addressing nutritional deficiencies, especially in urban areas where access to fresh produce is limited (Zhang *et al.*, 2021) (Seth *et al.*, 2025). Their incorporation into diets can enhance overall health and well-being, particularly among vulnerable populations. By providing essential nutrients that are often lacking in conventional diets. This underscores the importance of promoting microgreens as a viable solution for enhancing nutrition and health outcomes globally.

Conclusion

While microgreens present numerous benefits, challenges such as varying consumer awareness and income disparities can affect their market penetration. Additionally, the need for more in vivo and clinical trials to substantiate health claims remains a critical area for future research. Addressing these challenges through targeted research and strategic initiatives can enhance the role of microgreens in promoting sustainable, functional foods.

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FARMER PRODUCER ORGANIZATIONS AND AGRICULTURAL EXTENSION SERVICES IN INDIA: SYNERGY, CHALLENGES, AND STRATEGIES FOR SUSTAINABLE AGRICULTURAL DEVELOPMENT

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Abstract

Farmer Producer Organizations (FPOs) have emerged as a transformative institutional model for empowering smallholder farmers, enhancing market access, and promoting sustainable agricultural practices. Operating as farmer-led collectives, FPOs enable members to pool resources, improve bargaining power, and adopt innovative technologies. Agricultural extension services complement these efforts by providing technical guidance, training, and knowledge transfer, thereby bridging the gap between research and practice. This article explores the synergy between FPOs and extension services, identifies key challenges—ranging from financial constraints and limited market integration to organizational inefficiencies and climate change impacts—and proposes strategic interventions to enhance their effectiveness. Recommended strategies include awareness and capacity-building campaigns, dedicated financial mechanisms, modernization of extension systems, integration of digital technologies, and supportive policy frameworks aligned with current agricultural trends. By strengthening the collaboration between FPOs and extension services, India can foster resilient, competitive, and environmentally sustainable farming systems capable of meeting future food security and rural development goals.

Keywords: Farmer Producer Organization, Agricultural Extension, Sustainable Agriculture, Market Access, Rural Development, Policy Support

Introduction

In recent years, the agricultural landscape has undergone significant transformations, driven by the growing need for sustainable practices, economic viability, and food security. One of the most prominent institutional innovations in this context is the emergence of Farmer Producer Organizations (FPOs). An FPO is a farmer-led collective formed to leverage economies of scale in the production and marketing of agricultural and allied sector products. The term "FPO" is generic, referring to entities incorporated or registered either under *Part IXA of the Companies Act* or under the *Co-operative Societies Act* of the respective states. The primary aim of these organizations is to empower farmers through collective action, enabling them to overcome individual limitations, enhance bargaining power, and access better market opportunities. The concept behind FPOs is transformative-farmers, who are the producers of agricultural commodities, come together to form groups that can collectively address challenges in production, procurement, and marketing. By pooling resources, FPOs enable farmers to secure better prices, reduce transaction costs, and access modern technology, credit, and market intelligence. They operate on principles of democratic decision-making, inclusivity, and farmer empowerment, offering members—primarily smallholder farmers—a platform to discuss challenges, share experiences, and engage in capacity-building initiatives (Mohd. Ameer Khan et al., 2020). To promote their formation, the Small Farmers' Agribusiness Consortium (SFAC)—under the mandate of the *Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India*—supports State Governments in establishing FPOs. National-level agencies such as the National Agricultural Cooperative Marketing Federation of India (NAFED) also contribute to their promotion and capacity-building. Recognizing their potential, the Government of India has launched various initiatives to facilitate FPO growth, including financial assistance, technical guidance, and policy frameworks that promote access to credit, tax incentives, and market linkages (D. K. Krishna et al., 2018). The benefits of FPOs extend beyond economic gains. They actively promote sustainable agriculture and natural resource management, encouraging climate-smart practices, organic farming, and the judicious use of water, land, and other resources (Shwati Pardhi et al., 2021). Such environmentally responsible approaches contribute to the long-term viability of farming systems while preserving natural ecosystems. As of 2023, India is home to over 8,000 registered FPOs, representing millions of farmers across diverse agricultural sectors. This rapid expansion underscores the increasing acceptance of FPOs as a viable institutional mechanism for enhancing farmers' incomes, strengthening rural livelihoods, and promoting agricultural development. Overall, FPOs act as catalysts for transforming the agricultural sector, fostering rural prosperity, and building a sustainable future for smallholder farmers.

Synergy Between Farmer Producer Organizations and Agricultural Extension Services

Farmer Producer Organizations (FPOs) and agricultural extension services play complementary and mutually reinforcing roles in advancing agricultural development and improving farmer livelihoods. While FPOs aggregate farmers to facilitate collective action, enhance market access, strengthen bargaining power, and improve access to resources, agricultural extension services provide knowledge, training, and technical support to improve farming practices, productivity, and profitability. The synergy between the two lies in the ability of extension services to strengthen FPOs' capacity, while FPOs, in turn, extend the reach, relevance, and effectiveness of extension efforts. Extension services serve as a crucial link between agricultural research and on-ground farming practices, translating scientific advancements into practical, farmer-friendly solutions. They disseminate information on best practices, new technologies, pest and disease management, climate adaptation strategies, and market trends. When embedded within the organizational framework of FPOs, these services can ensure wider coverage, faster adoption, and greater impact on the farming community.

Key areas of synergy include:

1. **Capacity Building** – Extension services can train FPO members in sustainable agricultural practices, organic farming methods, efficient water and nutrient management, and climate-smart techniques.
2. **Market Linkages** – Extension agents can help FPOs identify profitable markets, understand demand trends, and connect with buyers.
3. **Access to Technology** – Extension systems can facilitate adoption of precision farming, mobile advisories, weather forecasting, and digital marketing.
4. **Policy Awareness and Advocacy** – FPOs can work with extension agents to understand policies, access schemes, and advocate for reforms.

Challenges Faced by Farmer Producer Organizations and Extension Services in the Current Scenario

Despite their potential, FPOs and extension services face several challenges:

1. **Organizational Limitations** – Weak governance, inadequate management skills, and low financial literacy.
2. **Financial Constraints** – Limited access to affordable credit and investment capital.
3. **Market Integration Issues** – Underdeveloped branding, value addition, and infrastructure.
4. **Extension Gaps** – Shortage of manpower, outdated methods, and poor digital integration.
5. **Low Technology Adoption** – Limited awareness, training, and affordability constraints.
6. **Policy and Regulatory Barriers** – Bureaucratic delays, inconsistent implementation, and policy uncertainty.
7. **Climate Change Impacts** – Unpredictable weather, water scarcity, and soil degradation.
8. **Member Participation** – Low awareness and delayed benefits affecting engagement.

Strategies to Maximize the Potential of FPOs and Extension Services

A multi-pronged approach is needed to address challenges and align with current agricultural trends:

1. **Awareness and Capacity Building** – Farmer education on FPO benefits, governance, and business planning.
2. **Financial Support** – Dedicated funds, low-interest credit, and fintech linkages.
3. **Modernized Extension Services** – Continuous training on climate-smart, market-oriented agriculture.
4. **Technology Integration** – Digital platforms, e-marketplaces, and precision farming tools.
5. **Policy Support** – Streamlined registration, tax benefits, and integration into national strategies.
6. **Trend Alignment** – Leveraging organic farming, farm-to-fork models, and value-added product markets.

Conclusion

Farmer Producer Organizations and agricultural extension services hold significant promise for transforming the Indian agricultural sector. Their combined strengths in collective action and knowledge dissemination can help smallholder farmers improve productivity, profitability, and sustainability. However, systemic challenges—financial, organizational, and policy-related—must be addressed through targeted interventions. Aligning these efforts with emerging agricultural trends such as sustainable intensification, digital agriculture, and value chain development will ensure that FPOs and extension services remain central to India's rural development and food security agenda.

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NEED OF CULTIVATION OF MEDICINAL AND AROMATIC CROPS AS AGRICULTURAL CROPS

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Abstract
Medicinal and aromatic plants (MAPs) play a vital role in healthcare, traditional medicine, and the phytopharmaceutical industry. With rising global demand, their sustainable cultivation has become critical to reduce dependence on wild collection and ensure consistent quality. Integrating MAPs into farming systems requires agro-ecological zoning, Good Agricultural Practices (GAP), and quality assurance mechanisms. However, challenges such as limited research support, lack of quality planting material, unstable markets, inadequate testing facilities and absence of clear quality standards hinder large-scale adoption. Addressing these barriers through research, policy support and market linkages can enhance economic viability and promote conservation while ensuring supply of high-quality raw materials. Thus, cultivation of MAPs as agricultural crops offers both ecological and economic opportunities if supported by systematic strategies.

Keywords: Medicinal and aromatic plants (MAPs), Good Agricultural Practices, cultivation, agricultural crops

Introduction
India is home to diverse range of medicinal plants which have been used for centuries by the local people to meet not only their own primary health care needs but also to address ailments of domesticated animals and crops. Nowadays, the indulgence towards herbal medicines is increasing; some of the reasons are: i) The realization that allopathic drugs have harmful side-effects. ii) Allopathic medicines are said to be ineffective against many chronic diseases like cancer. Moreover, many people suffering from diabetes, arthritis, respiratory diseases, skin ailments, gastric problems, jaundice, etc. are said to be turning more and more to Ayurveda and Unani for permanent cures. iii) Herbal medicines are comparatively less expensive. iv) The western medical profession has begun to acknowledge the value of herbal medicines.The market for herbal medicines in the developed countries is growing at a faster rate than other pharmaceutical products. Recently, cultivation of MAPs has started gaining momentum, still a significant part of our requirements continues to be met from wild. Though, the tribal belt of India is rich MAPs and mainly depends on collection and trade for their livelihood, the supply of raw material for the industry is procured through minor forest produce contractors/dealers (Farooqi& Sreeramu, 2004; Singh *et al*., 2022).

Need for cultivation of MAPs

- **Best variety cultivated to obtain raw material of homogenous quality and high potency:** In nature there remains a wide variation among the plants with regard to their active principles. As only the best among them is used for cultivation, it enables us to obtain raw material of homogenous quality and high potency.
- **To fulfil the demands of large-scale supply:** It is easy to grow and fulfil the commitment of large-scale supply through cultivated sources rather than from natural sources which mainly depend on nature for their regeneration and availability

- **Sustained availability of quality herbs:** The growing pressure of population/urbanization and the development of roads to remote areas has resulted in deforestation and the loss of natural plant resources. Hence, cultivation of such plants as agricultural crops could be utilized perpetually.
- **To engage in GACP of MAPs:** As in many cases, as the important plant parts used are roots or the entire plant, this results in plant collectors engaging in destructive collection/extractive methods, resulting in many plants becoming extinct or being listed as threatened.
- **Conservation of biodiversity:** Despite the fact that our forests are a major resource-base for medicinal plants as many of them appear in the wild, the importance of this has not been totally appreciated by the concerned government departments. So much so, that many forest action plans do not clearly spell out any long-term strategy for the conservation of biodiversity and support to the communities which are solely dependent on forests for their livelihood
- **To reduce unauthorized collection of minor forest produce from wild:** The unauthorized collection of minor forest produce by persons who are led by the burgeoning demand for raw medicinal plant parts has led to the deprivation of the rights and opportunities of the forest-dwelling communities.

Opportunities

- **Indigenous traditional knowledge and vast biodiversity range of India:** India, with its vast biodiversity and potential for commercial exploitation, could become a world leader in the supply of raw material for the phytopharmaceutical industry
- **By cultivation and conservation of medicinal plants in league with the forest departments outline many threats**: By drawing up a comprehensive strategy for the cultivation and conservation of medicinal plants in league with the forest departments, many threats outlined earlier could turn into opportunities for successful commercial exploitation without tampering with the interests of the communities involved in the collection of medicinal plants.
- **Soil and water conservation by MAPs cropping in farms:** The introduction of medicinal plants into the cropping patterns of farming communities, especially in dryland and watershed areas could provide a strong thrust to the need for soil and water conservation, as well as provide returns and indirectly help in ex situ conservation of these crops to a significant extent.

Future Prospects

- Harvesting medicinal plants is more economical than artificial drug synthesis.
- Demand for Indian-origin phyto-pharmaceutical herbs is rising globally, alongside growing domestic needs for raw materials in perfumery, pharmacy, and biopesticide industries.
- Traditional herbal drugs are gaining popularity due to the side effects of synthetic drugs and the expansion of natural drug-based pharmacies.
- India faces a significant supply–demand gap in phytopharmaceutical products, leading to heavy drug imports. Import substitution through domestic production of raw materials and fine chemicals is essential.
- Many medicinal and aromatic plants (MAPs) are hardy, perform well on marginal lands, resist cattle damage/pilferage, and can be integrated as intercrops, mixed crops, or undercrops.
- India holds a rich medical heritage through Ayurveda, Unani, and Siddha systems, offering a strong foundation for medicinal plant cultivation.

Constraints

- **Lack of research support**: No organized system to provide continuous scientific inputs for making cultivation economically viable.
- **Limited inputs & infrastructure**: Scarcity of quality planting material, improved varieties, extension literature, training, and testing facilities—except limited efforts by CIMAP and a few ICAR centers.
- **Market instability**: Price fluctuations due to quality-based pricing, absence of testing at procurement/trading centers, and poor market handling discourage farmers.
- **Absence of quality standards**: No fixed benchmarks for raw materials or final products in the phytopharmaceutical industry, leading to inconsistent quality.
- **Storage issues**: Plant products have short shelf life (5–6 months); fumigation to extend storage risks chemical contamination.
- **Landholding & crop constraints**: Small, fragmented holdings restrict large-scale cultivation; many key medicinal plants (e.g., amla, asoka, arjun, bael, nutmeg, neem) have long gestation periods, deterring farmers.

PRE-REQUISITE FOR THE CULTIVATION OF MAPs

Before starting commercial cultivation of medicinal plants, it is essential to understand agro-ecological zoning, Good Agricultural Practices (GAP), quality targets, and agro-economics (Atheequlla *et al.*, 2021). The first step is selecting suitable crops for the right locations, guided by regional climatological conditions and GIS-based mapping. GAP ensures the production of high-quality raw materials, while mapping of critical materials and processes helps assess cultivation risks. Finally, cost–return analysis, market assessment, and supportive policy frameworks are necessary to promote sustainable and profitable medicinal crop cultivation.

Conclusion

The success of medicinal plants sector mainly depends on the awareness and interest of the farmers as well as its other stakeholders, supportive government policies, availability of assured markets, profitable price levels, and assess to simple and appropriate agro-techniques. Thus, needs to focus on both cultivation and collection, together with R&D, promotion and information for procurement of MAPs, ensuring Minimum Support Price, setting up networked Agri-Mandis for MAPs, drawing up a database of cultivators and growers / cooperatives.

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OCEAN ACIDIFICATION AND ITS SYNERGISTIC EFFECTS ON CORAL CALCIFICATION AND REPRODUCTION

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Abstract
Warm-water coral reefs, primarily formed by calcifying scleractinian corals, are among the most biologically diverse and ecologically significant marine ecosystems on the planet. These reefs provide essential ecosystem services, including coastal protection, fisheries, and tourism revenue. However, rising atmospheric CO_2 levels have triggered ocean acidification (OA), which lowers seawater pH and reduces carbonate ion availability, threatening coral calcification and reproduction. While some coral species show physiological resilience, population-level impacts—including reduced skeletal density, impaired fertilization, and compromised recruitment—pose significant risks to reef persistence. Ocean acidification interacts synergistically with other stressors such as warming, eutrophication, and hypoxia, compounding the degradation of coral reef ecosystems. The resulting loss of biodiversity and ecosystem function has far-reaching ecological and socioeconomic implications, particularly for coastal and island communities. This paper reviews the mechanisms of OA, its effects on coral calcification and reproduction, and highlights the importance of integrated mitigation and adaptation strategies, including global CO_2 reduction, local stressor management, and emerging approaches in coral restoration and assisted evolution.

Introduction
Warm-water coral reefs are vital ecosystems located in alkaline, and nutrient-poor coastal waters of the Pacific, Indian, and Atlantic Oceans, typically between 30°S and 30°N. These reefs are primarily formed by reef-building scleractinian corals that deposit large amounts of calcium carbonate. Over time, dead coral skeletons accumulate and are cemented by other organisms like encrusting red coralline algae. Calcifying green algae, zooplankton, and phytoplankton also contribute to the reef's carbonate budget, resulting in complex three-dimensional structures that evolve over hundreds to thousands of years. These structures create habitats for vast biodiversity, supporting thousands of marine species and providing crucial ecosystem services, including food, income, coastal protection, and biomedical resources for human populations. Ocean acidification (OA), driven by increasing atmospheric CO_2 concentrations, is a major component of ongoing global environmental change. As oceans absorb more CO_2, their pH decreases—already by 0.1 units since the Industrial Revolution—with projections indicating an additional 0.3–0.32 unit decline by the end of this century. This pH reduction alters the availability of carbonate and bicarbonate ions essential for the calcification processes in marine organisms. As a result, OA poses a significant threat to calcifying organisms like scleractinian corals, reducing their ability to form skeletons and affecting reproduction, growth, and overall reef resilience. Coral reefs are thus among the most vulnerable ecosystems to acidification, and the physiological disruptions may lead to cascading effects throughout the reef ecosystem. This

paper provides a concise overview of the direct physiological impacts of OA, along with a detailed examination of its broader ecological effects on shallow-water tropical and temperate corals, offering insight into the potential future of coral reefs under increasingly acidified ocean conditions.

Keywords: ocean acidification, Coral reproduction, Climate change, Synergistic stressors, Coral bleaching, Marine ecosystems, Coral resilience and Coral reef degradation,

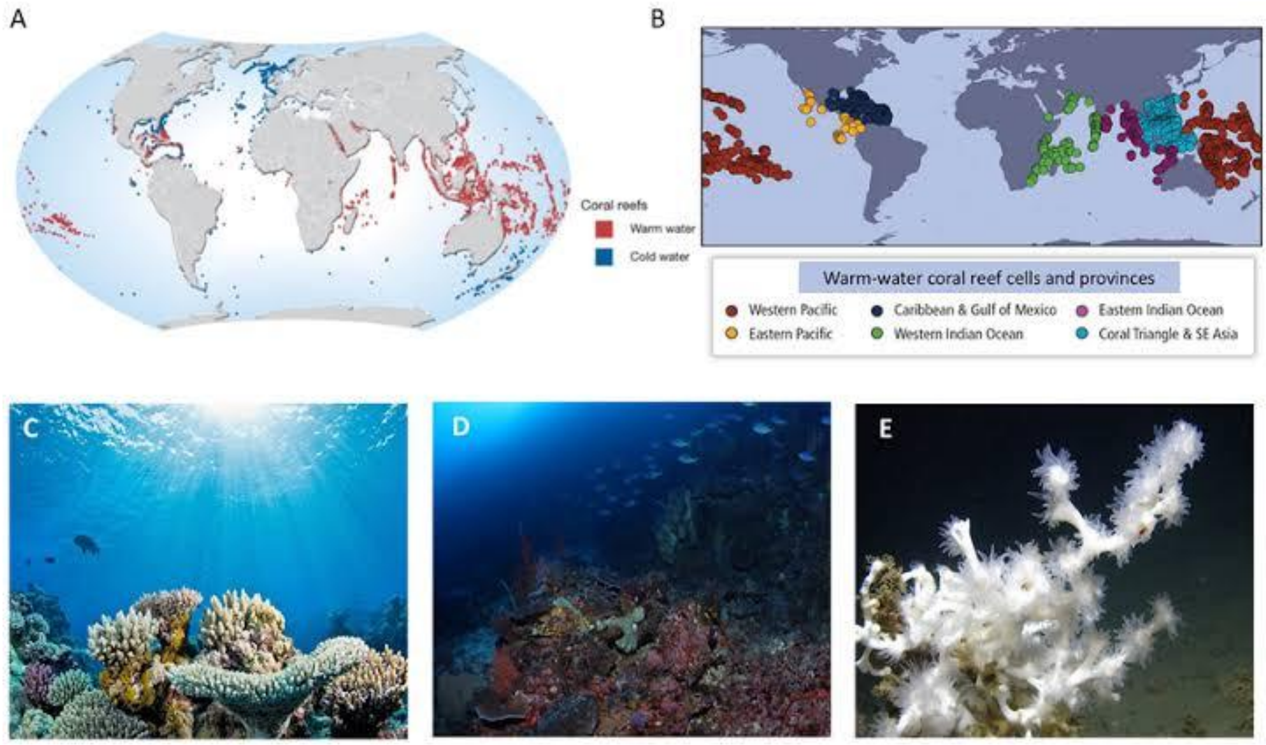

FIGURE-1
(A)Distribution of warm-water and cold-water coral reefs(credit:HugoAhlenius,2008,UNEP/GRIDArendal,http://www.grida.no/resources/7197).
(B)Location of warm-watercoral reefcellsandprovinces, fromHoegh-Guldbergetal. (2014).
(C)Warm-watercarbonatecoral reef fromtheGreatBarrierReef,Australia(credit:OveHoegh-Guldberg).
(D)MesophoticcoralcommunityofNorthSulawesi,Indonesia.(Credit:PimBongaerts,UniversityofQueensland).
(E)Deep-watercommunityofLopheliapertusafromtheMississippiCanyonat~450mdepth(ImagefromNOAA, licensedundertheCreativeCommonsAttribution-ShareAlike2.0 Genericlicense).

Effects of ocean Acidification on coral

Corals use various stress responses across multiple biological levels—from molecular and cellular mechanisms to whole-organism and population-level adjustments—to cope with ocean acidification. These physiological processes, such as internal pH regulation during calcification are energetically demanding but don't always deplete energy reserves allowing some species to sustain growth even under acidified conditions. At the colony level, ocean acidification shows mixed impacts on photosynthesis and calcification: most studies report no significant change in photosynthetic rates, symbiont density, or chlorophyll concentration. Although declines in calcification are, responses vary by species and colony, with many showing no significant effect. Some corals even continue to calcify in naturally low-pH environments, well below laboratory thresholds.

Population-level impacts are clearer: small physiological changes accumulate across individuals, affecting population dynamics. Corals may shift from producing dense skeletons to faster-growing but weaker ones, increasing breakage risk. Alternatively, some maintain skeletal integrity at the cost of slower growth, which can reduce reproductive output by preventing colonies from reaching high-fecundity sizes. Early reproductive stages are generally resilient, but settlement and recruitment are more vulnerable, with up to 52% reductions expected mid-century and up to 91% by century's end—potentially reducing coral cover by 15% over seven years.

Adult survival shows little consistent decline; rather, sub-lethal effects—like reduced growth or reproduction—are more common. These cumulative stressors may hamper population growth, altering abundance, diversity, and community composition at ecosystem scales. Notably, 52% of observations report no significant change under acidification; negative effects are seen more frequently at the population level (26%) than at colony (16%) or cellular (10%) levels. This suggests that while individual corals often survive stress, populations may decline, underscoring the need for research focused on demographic and community responses, not just individual physiology. Beyond direct effects, acidification also disrupts ecological interactions—altering behaviors, species interactions, and community dynamics—though these complex, indirect effects are hard to predict.

Impact on coral calcification

Calcification is a critical process by which reef-building corals deposit calcium carbonate ($CaCO_3$), primarily in the form of aragonite, to construct their skeletons. This energy-intensive mechanism is highly sensitive to changes in seawater chemistry. Ocean acidification, driven by elevated atmospheric CO_2, reduces the saturation state of aragonite, leading to slower skeletal growth and weakened structural integrity. Empirical studies have confirmed this relationship reported that a 0.3 unit decline in seawater pH could cause a 20–60% reduction in coral calcification rates. Prolonged exposure to acidified conditions not only diminishes calcification but also alters skeletal density and morphology, increasing coral vulnerability to bioerosion and physical damage from storms.

Impact on Coral Reproduction

Ocean acidification impacts coral sexual reproduction, Studying gametogenesis is challenging due to its long duration (9–11 months in some species) and experimental constraints. However, some studies suggest gamete production may resist acidification. For instance, Montipora capitata and species like *Oculina patagonica* and *Madracispharensis* showed normal gametogenesis under low pH. Yet, spawning female corals appear more affected than males, possibly due to the high energy cost of egg production impairing calcification. Fertilization studies reveal elevated pCO_2 can reduce fertilization success in corals (*Acropora palmata, Montastraea faveolata*) and other invertebrates like oysters and urchins, with effects depending on sperm concentration. In *A. palmata* and *M. faveolata* fertilization declined under acidification when sperm levels were below optimal (~10^6 sperm/mL). Similar sperm concentration-specific effects were observed in urchins (*Strongylocentrotus franciscanus*), where acidification increased sperm limitation and susceptibility to polyspermy. However, some species like *Crassostrea gigas* and *Heliocidaris erythrogramma* show resistance.

Differences among studies may stem from species-specific sensitivities and methodological variability. Fertilization success depends on factors like sperm-egg contact time, compatibility, aging, motility, and concentration. Most studies only report sperm concentration, yet using a single, often "optimal," level limits ecological relevance. In nature, sperm concentrations are highly variable. For example, concentrations near 10^6 sperm/mL were observed shortly after coral spawning but declined rapidly within hours.

Mechanistically, acidification may reduce fertilization by affecting sperm or egg physiology. For corals and other invertebrates, reduced intracellular pH can impair sperm motility. Acidified conditions decrease flagellar activity in Acropora digitifera and other species, possibly by interfering with [pH]. Some, like *C. gigas*, are unaffected. Fertilization potential of eggs may also decline due to changes in [pH]i or increased polyspermy, particularly since coral eggs lack protective fertilization membranes. Historical studies in sea urchins and marine worms have linked low pH to higher polyspermy and fertilization failure. Overall, acidification may impair early fertilization stages, especially in taxa without mechanisms to block multiple sperm entries.

Synergistic stressors

Ocean acidification rarely acts in isolation. Combined with other anthropogenic stressors—such as ocean warming, eutrophication, and hypoxia—OA amplifies negative impacts:

- Warming exacerbates thermal stress, leading to bleaching and impaired energy allocation for reproduction and calcification.
- Eutrophication from coastal runoff promotes algal overgrowth, which competes with coral larvae for space and light.
- Hypoxia impairs coral respiration, and when coupled with OA, can lead to widespread mortality.

The synergistic interaction between these stressors results in non-linear, often unpredictable outcomes. For example, found that the combined effect of warming and OA reduced coral resilience more than either stressor alone.

Ecological and Socioeconomic Implications

The reduction in coral calcification and reproductive capacity threatens reef accretion, biodiversity, and vital ecosystem services. As reef structures deteriorate, habitat complexity declines, adversely impacting fish populations and the livelihoods that depend on them. Globally, coral reefs generate approximately USD 36 billion annually through tourism, fisheries, and coastal protection. Consequently, reef degradation driven by ocean acidification poses serious risks to food security and the economic stability of coastal and island communities, particularly in developing nations.

Mitigation and Adaptation Strategies

Efforts to mitigate the impacts of ocean acidification (OA) must begin with global-scale initiatives, primarily focusing on the reduction of atmospheric CO_2 emissions—the root cause of OA. Central to this goal are international agreements such as the Paris Agreement, which aims to limit global warming to below 2°C, preferably 1.5°C above pre-industrial levels. Achieving this target requires a drastic decline in fossil fuel use, increased reliance on renewable energy sources, and widespread implementation of carbon capture and storage (CCS) technologies.

At the local and regional level, adaptive strategies are essential for buffering marine ecosystems, particularly coral reefs, against OA-related stressors. These strategies include improving coastal water quality, curbing nutrient runoff from agriculture and urbanization, and mitigating other local stressors like overfishing and sedimentation. Implementation of marine protected areas (MPAs) provides ecological sanctuaries where biodiversity can flourish, thereby increasing ecosystem resilience.

Emerging techniques in coral restoration and assisted evolution hold great potential to support reef adaptation under changing ocean conditions. Methods such as selective breeding of stress-tolerant genotypes, assisted gene flow, probiotic manipulation of the coral microbiome, and preconditioning corals through environmental hardening are being tested to increase coral resistance to both acidification and thermal stress. These approaches aim to accelerate natural evolutionary processes and enhance the adaptive capacity of coral holobionts.

Innovative geoengineering solutions, such as alkalinity enhancement using olivine or calcium carbonate, are also being explored to locally raise seawater pH and counteract acidification effects on sensitive habitats. While these interventions are still under research, they highlight the need for multifaceted strategies combining emission reductions with localized adaptation.

Conclusion

Ocean acidification is a critical and accelerating threat to coral reef ecosystems, undermining their structural integrity, reproductive success, and resilience in the face of environmental change. While individual coral colonies may demonstrate varying degrees of tolerance, population-level effects—including declines in recruitment, growth, and genetic diversity—indicate that coral reefs face a challenging future under continued acidification. When compounded by warming, nutrient loading, and other stressors, the synergistic effects can lead to rapid and potentially irreversible reef degradation. Mitigating OA requires urgent global action to curb CO_2 emissions, supported by local interventions to reduce additional stressors and enhance ecosystem resilience. Promising innovations in coral adaptation—such as assisted evolution and microbiome manipulation—must be advanced alongside traditional ecological knowledge and community-based management. Only through a multifaceted and collaborative approach can we hope to preserve coral reefs and the invaluable services they provide to both marine life and human societies.

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POLLINATOR CONSERVATION IN AGRICULTURAL LANDSCAPES: A COMPREHENSIVE FRAMEWORK FOR SUSTAINABLE FOOD SECURITY

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Abstract

Pollinators, mainly insects, are crucial for global food security and the health of ecosystems. However, agricultural landscapes, despite being vital for human sustenance, often pose significant threats to pollinator populations. These threats include habitat loss, pesticide use, and monoculture practices. This article explores the critical role of pollinators, the challenges they face in agricultural settings, and the various conservation strategies being implemented to protect them. It also emphasizes the importance of integrating pollinator-friendly practices, such as creating diverse floral resources, reducing pesticide exposure, and fostering diversified farming systems, to support both pollinator populations and agricultural productivity.

Introduction: The Unsung Heroes of Our Food System

The global food system and the diversity of life on Earth rely heavily on pollinators. These organisms, which are primarily insects such as bees, butterflies, moths, beetles, and flies, help reproduce nearly 90% of the world's wild flowering plants and contribute to the production of over 75% of the leading global food crops. Pollinator decline is a global crisis largely caused by pressures from human activities. While agriculture is essential for producing food, it paradoxically depends on pollinators while often being hostile to their survival. From the apples in our lunchboxes to the coffee in our morning cups, the intricate dance between flower and pollinator underpins a significant portion of our dietary staples and agricultural economy. Conserving pollinators in these landscapes is crucial for preserving biodiversity and ensuring long-term food security for a growing global population.

The economic value of pollinators is staggering, with their services contributing an estimated $235–577 billion annually to global agricultural production, which is about 9.5% of the total agricultural value. Pollinator limitation affects up to 60% of global crop systems, with 25 of 49 crop species experiencing yield deficits due to insufficient pollination. For instance, in the Himalayan region of Nepal, honeybee populations in occupied beehives declined by 44% and honey production per hive by 50% between 2012 and 2022. Similarly, in the U.S., pesticide use has been a major factor in the decline of wild bee species, with some families experiencing up to a 43.3% decrease in site occurrence probability.

The Indispensable Role of Pollinators in Agriculture

Pollinators provide a vital ecosystem service by transferring pollen between flowers, enabling fertilization and the setting of fruit or seeds. This service translates directly into increased crop yields, improved fruit quality, and enhanced genetic diversity in agricultural systems.

- **Crop Dependence:** Many economically important crops depend on animal pollination, including fruits like almonds, blueberries, and apples, vegetables like cucumbers and squash, and oilseeds such as canola and sunflower. Without effective pollination, the productivity of these crops can plummet, causing significant economic losses for farmers and higher food prices for consumers.
- **Yield and Quality Enhancement:** Beyond just enabling fruit set, adequate pollination leads to larger fruits, more uniform ripening, and higher seed viability. For example, well-pollinated strawberry flowers produce larger, more symmetrical berries.
- **Genetic Diversity:** Pollinators facilitate cross-pollination, which promotes genetic exchange within plant populations. This genetic diversity is essential for plants to adapt to changing environmental conditions, resist diseases, and evolve new traits, thereby enhancing agricultural resilience against threats like climate change.

Threats to Pollinators in Agricultural Landscapes

The decline of pollinator populations is a complex issue, with agricultural practices being a central factor in several key threats.

Habitat Loss and Fragmentation

Intensive agriculture often involves converting diverse natural habitats like meadows and hedgerows into vast monocultures. This leads to:

- **Loss of Floral Resources**: Monocultures, which flower for only a short period, create "floral deserts" for much of the year, leading to starvation for pollinators who need a continuous supply of nectar and pollen.
- **Loss of Nesting and Roosting Sites**: The removal of non-crop vegetation, tilling, and tidying of agricultural land destroy critical nesting and roosting sites for bees and butterflies.
- **Habitat Fragmentation**: Remaining small patches of habitat can become isolated, making it difficult for pollinators to move between them, which reduces gene flow and increases vulnerability to local extinction. Studies have shown that corridors can restore animal-mediated pollination, with connected patches having 14.3 times higher forest-associated pollinator availability compared to isolated ones.

Pesticide Use

The widespread use of pesticides is a primary driver of pollinator decline.

- **Direct Toxicity**: Insecticides are designed to kill insects and can directly poison pollinators through contact, ingestion of contaminated pollen or nectar, or exposure to residues.
- **Sublethal Effects**: Even in small doses, pesticides can impair navigation, reduce foraging efficiency, weaken immune systems, and decrease reproductive success. Neonicotinoid insecticides, in particular, are a continuous threat due to their systemic and persistent nature.
- **Synergistic Effects**: Pollinators are often exposed to multiple pesticides, leading to combined toxicity that is greater than the sum of their individual effects. Fungicides, which are often thought to be harmless to insects, can also amplify the toxicity of insecticides to bees. Pesticide drift is also a threat, as chemicals can accumulate in bee-collected pollen and wax even when not directly applied to the plants.

Disease and Parasites

Intensive agriculture can worsen the spread and impact of diseases and parasites. The stress from habitat loss and pesticide exposure can weaken pollinator immune systems, making them more susceptible to pathogens like the gut parasite - *Nosema ceranae* or the *Varroa* mite in honey bees.

Climate Change

Climate change interacts with agricultural practices to harm pollinators. Shifting flowering times due to warmer temperatures can cause a "phenological mismatch," where pollinator emergence no longer aligns with the availability of their food sources. Pollinator abundance is 61.1% lower in cropland experiencing novel temperatures compared to natural habitats that have not seen temperature increases. Climate change is considered the most prominent and challenging threat to control.

Strategies for Pollinator Conservation in Agricultural Landscapes

Addressing pollinator decline requires a multi-faceted approach that integrates ecological principles into agricultural management.

Enhancing Habitat and Floral Resources

Creating and restoring diverse habitats within and around agricultural fields is fundamental.

- **Flower Strips and Hedgerows**: Planting strips of native flowering plants along field margins provides crucial nectar and pollen resources throughout the growing season and offers nesting sites and shelter.
- **Cover Cropping and Intercropping**: Using flowering cover crops like clover or intercropping diverse plant species can increase floral diversity, reduce soil disturbance, and provide continuous resources.
- **Nest Site Provision**: Leaving areas of undisturbed bare ground for ground-nesting bees and providing bundles of hollow stems for cavity-nesting bees can enhance nesting opportunities.

Reducing Pesticide Exposure

Mitigating the impact of pesticides is crucial and involves shifting towards sustainable pest management strategies.

- **Integrated Pest Management (IPM)**: IPM is a holistic approach that prioritizes non-chemical methods. It includes monitoring pest levels, using biological controls (e.g., predatory insects) , employing cultural practices like crop rotation , and using targeted pesticide application.
- **Integrated Pest and Pollinator Management (IPPM)**: This approach explicitly incorporates pollinator conservation into pest control decisions. IPPM strategies include timing pesticide applications to avoid pollinator foraging periods and establishing buffer zones around sensitive habitats.

Diversified Farming Systems

Moving away from large-scale monocultures towards diversified farming systems benefits pollinators and enhances overall agricultural resilience.

- **Crop Rotation**: Rotating different crops breaks pest cycles and provides a more varied sequence of floral resources.
- **Agroforestry**: Integrating trees and shrubs into agricultural landscapes creates complex habitats, offers shelter, and provides diverse food sources for pollinators.
- **Organic Farming**: These systems often support higher pollinator diversity due to reduced chemical use and greater plant diversity.

Policy and Economic Incentives

Government policies and economic incentives are vital for promoting pollinator-friendly practices.

- **Conservation Programs**: Subsidies and payments encourage farmers to create pollinator habitats and reduce pesticide use. In the U.S., the Environmental Quality Incentives Program (EQIP) and the Conservation Reserve Program (CRP) provide incentive payments and prioritize pollinator habitat creation. The European Union's Common Agricultural Policy (CAP) and its Eco-schemes also allocate funds to support pollinator habitat.
- **Economic Viability**: Pollinator habitat can be financially viable for farmers, as research on native wildflower strips shows that seed sales revenue can exceed establishment costs. Pollinator-friendly practices also provide synergistic benefits, such as enhanced natural pest control and improved soil health.

Conclusion: A Shared Future

Pollinator conservation in agricultural landscapes is an ecological imperative and an economic necessity for global food security. By adopting a suite of integrated strategies enhancing diverse habitats, carefully managing pesticide use, and fostering diversified farming systems we can transform agricultural landscapes from zones of threat into havens of biodiversity. This transformation requires collaborative efforts from policymakers, researchers, farmers, and consumers. The future of our food system depends on the health of pollinators. By protecting them, we ensure their survival and the continued productivity of our farms and the resilience of our planet's food systems for generations to come.

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PACU FARMING: SUSTAINABLE PRACTICES AND FUTURE POTENTIAL IN GLOBAL AQUACULTURE

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Abstract
Pacu farming has gained increasing importance as a sustainable and profitable practice in the aquaculture industry. Native to South America, Pacu are large omnivorous fish known for their adaptability, rapid growth, and high demand in both ornamental fish trade and food industries. With species like *Colossoma macropomum* (Tambaqui) and *Piaractus brachypomus* (Red-bellied Pacu), the farming of Pacu offers a viable solution to meet the growing global demand for fish protein. Successful Pacu farming relies on maintaining optimal water quality, managing breeding cycles through artificial techniques, and ensuring a diet that mimics their natural intake. Various farming systems, such as pond culture, cage farming, and Recirculating Aquaculture Systems (RAS), provide flexibility in operation. The future of Pacu farming looks promising with continued advancements in sustainable practices and technologies, helping to minimize environmental impact and support local economies while addressing food security challenges worldwide.

Key words: Pacu farming, Sustainable practices, Behaviour of fishes, Artificial Breeding Technique, Challenges.

Introduction
Pacu (genus *Colossoma* and *Piaractus*) is a large freshwater fish species from the Characidae family, closely related to the piranha. Native to South American river systems such as the Amazon and Orinoco basins, Pacu are well known for their deep, laterally compressed bodies, strong jaws and distinctive appearance, which resembles that of their more famous relatives, the piranhas. However, unlike piranhas, Pacu are omnivores and have a much gentler temperament, feeding on a wide range of fruits, seeds, nuts and aquatic plants. These fish grow to impressive sizes, reaching length up to 3 feet (90 cm) and weights of up to 55 pounds (25 kg). Due to their large size, distinct appearance and adaptability to various aquatic environments, Pacu are highly valued both as ornamental aquarium fish and as a food source in the aquaculture industry. In recent years, Pacu farming has gained importance, especially in countries like Brazil, Colombia and Venezuela, where they have become a staple protein source and an export commodity.

Importance of Pacu Farming
Pacu farming has grown substantially in recent decades. The fish's fast growth rate, adaptability to a range of aquaculture systems and high demand in both the ornamental fish trade and the food industry make it an attractive species for farming. In South America, particularly in Brazil and Colombia, Pacu farming has supported local economies, providing a sustainable source of protein for both local consumption and international export. As global demand for fish increases and wild

fisheries face greater environmental pressures, Pacu farming presents a viable alternative to meet this demand sustainably. Advancements in farming practices, such as Recirculating Aquaculture Systems (RAS) and the use of cage farming, have enabled farmers to optimize production while managing water quality more efficiently. However, as with any farming practice, challenges remain, particularly related to breeding, maintaining genetic diversity and optimizing feed practices to enhance fish health and growth rates. Nonetheless, the future of Pacu farming looks promising, especially with on-going improvements in sustainable farming methods.

Different Types of Pacu:

1. ***Colossoma macropomum* (Tambaqui)**: The largest of the two species, the Black Pacu can grow up to 3 feet (90 cm) and weigh as much as 55 pounds (25 kg). These fish are typically dark-coloured, ranging from black to gray and are known for their powerful jaws that can crush nuts and seeds. They inhabit large, slow-moving rivers and floodplains, often found in deeper water channels.
2. ***Piaractus macropomum* (Black Pacu):** *Piaractus macropomum* (Black Pacu) is a large, peaceful omnivorous fish native to South America's Amazon and Orinoco basins. It is highly valued in aquaculture for its rapid growth, reaching up to 3 feet in length and 55 pounds. Black Pacu are farmed for food and ornamental purposes, thriving in pond, cage and recirculating systems. They feed on fruits, seeds and commercial pellets and are known for their mild, white flesh.
3. ***Piaractus brachypomus* (Red-bellied Pacu)**: Smaller than the Black Pacu, the Red-bellied Pacu reaches up to 2 feet (60 cm) in length and weighs about 15-20 pounds (7-9 kg). It is easily recognizable by its reddish belly and is typically found in shallow river areas. The Red-bellied Pacu is popular in both the ornamental fish trade and as a food source due to its smaller size and vibrant coloration.

Behaviour and Diet

Pacu are omnivores, meaning their diet consists of both plant and animal-based materials. In their natural habitat, Pacu feed on fruits, seeds, nuts and aquatic plants. Their strong jaws are well adapted for cracking open hard seeds and nuts, which are a significant portion of their diet. Additionally, they feed on a variety of tropical fruits, including bananas, guavas and papayas, which provide essential vitamins and sugars. They also consume aquatic vegetation like water lilies and submerged plants, providing fibre and additional nutrients. In aquaculture, it is important to replicate pacu natural diet as closely as possible to ensure optimal health and growth. Farmers typically provide pelleted feeds that are specially formulated to meet the nutritional needs of the fish at different life stages. These feeds are supplemented with fresh fruits and vegetables like sweet potatoes, bananas and squash to provide natural sugars and fibre. While Pacu are primarily herbivorous, they also require small amounts of animal-based proteins, such as fishmeal or insect larvae to support growth and reproduction.

Breeding of Pacu

Breeding Season and Conditions

Pacu breeding is highly dependent on environmental factors. In the wild, they are seasonal spawners, with breeding occurring during the rainy season. This period is marked by rising water levels, which provide ideal conditions for reproduction. The influx of nutrient-rich water supports the growth of algae and other organisms, which, in turn, provides ample food for the fish and their larvae. The optimal temperature for breeding Pacu is between 25°C and 30°C (77°F to 86°F), with water pH levels between 6.5 and 7.5. The flow of water during the rainy season is essential to their breeding behaviour, as it creates the perfect conditions for spawning. Pacu typically migrate from deeper river channels to flooded forest areas to lay their eggs. The fish breed in large schools, with both males and females involved in the spawning process. A single female can release thousands of eggs during each spawning event.

Artificial Breeding Techniques

Artificial breeding has become a common practice in aquaculture to control the timing of reproduction and maximize productivity. Hormonal treatments are used to induce spawning, with hormones like human chorionic gonadotropin (hCG) and luteinizing hormone-releasing hormone (LHRH) analogs being commonly employed. These hormones stimulate ovulation and sperm release, allowing for controlled fertilization of the eggs. Once fertilized, the eggs are carefully collected and incubated in optimal conditions, which include maintaining the appropriate water temperature and oxygen levels. Artificial breeding ensures that the fish population remains stable and that genetic diversity is maintained through selective breeding programs. However, challenges remain in ensuring consistent spawning success and overcoming the inherent difficulties of replicating the ideal environmental conditions required for breeding.

Rearing of Pacu

Pacu farming requires careful management of water quality, including maintaining oxygen levels between 5–7 mg/L, a temperature range of 25°C–30°C and a pH level between 6.5 and 7.5. Fry are initially nourished by yolk sacs and need high-quality water to thrive. As they grow into juveniles, they require high-protein diets to support rapid development, while adults can be fed a more plant-based diet supplemented with protein like fishmeal. Feeding schedules should be followed carefully, with juveniles fed 3-4 times daily and adults once or twice per day. Overfeeding should be avoided to prevent excess waste and water contamination. Regular water changes and filtration are crucial to maintaining a healthy environment. Pacu farming can benefit from modern systems like Recirculating Aquaculture Systems (RAS), which allow for better water control and sustainability. In addition, Pacu farming should use a variety of foods, including fresh fruits and vegetables, to closely replicate their natural diet. Monitoring feed consumption and water quality regularly ensures optimal fish health and growth. Proper space management is key to preventing overcrowding, which can lead to poor growth and disease outbreaks. By adhering to these best practices, Pacu can be successfully farmed with minimal environmental impact.

Pacu Farming Systems

Pacu farming can be done through various systems, each offering unique advantages and challenges. Pond culture, the traditional and most widely used method, involves raising Pacu in large ponds, providing them with ample space to grow. While it is cost-effective, it requires careful management of water quality and can be labour-intensive. Cage farming involves raising Pacu in floating cages placed in natural water bodies like rivers, lakes, or reservoirs. This system offers better environmental control than pond culture but demands precise management of feed and water quality to avoid contamination. The more modern Recirculating Aquaculture Systems (RAS**)** filter and reuse water, making them particularly suitable for areas with limited water resources. Though the initial investment is higher, RAS provides superior control over water quality, reduces environmental impact and supports year-round production, making it a sustainable choice for Pacu farming.

Sustainability and Environmental Impact

Pacu farming must focus on **sustainable practices** to avoid water pollution and ecological degradation. Using **organic feed,** implementing **waste recycling systems** and reducing **water use** are essential. **Integrated multi-trophic aquaculture (IMTA),** where different species are farmed together, is an emerging solution to improve sustainability.

Challenges and Solutions

Health management is a key challenge in Pacu farming, with common issues like **fungal infections** and **parasites.** Maintaining **optimal water quality,** controlling **stock density** and using **biosecurity measures** can mitigate these risks. Economic viability depends on factors like **feed costs** and **market trends** and farmers must adhere to **regulations** on **water use, genetic diversity** and **waste management** for long-term profitability.

Conclusion

Pacu farming holds significant potential as a sustainable and profitable practice in the global aquaculture industry. With on-going advancements in breeding, rearing and farming technologies, Pacu farming ensuring water quality and managing health risks, Pacu farming can continue to thrive and become can meet the increasing demand for fish protein while minimizing environmental impact. By adopting sustainable farming practices, a key player in the future of global food production.

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PANCHAYATI RAJ INSTITUTIONS: PILLARS OF RURAL DEVELOPMENT IN INDIA

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Abstract

Panchayati Raj Institutions (PRIs) serve as the foundation of democratic decentralization and local self-governance in India. Envisioned as instruments to empower rural communities, PRIs bring governance closer to the people by enabling them to participate in decision-making processes that directly impact their daily lives. These institutions form a three-tier structure village, block, and district levels, ensuring representation from all segments of society, including women and marginalized groups. Through their active role in planning, implementing, and monitoring development programmes, PRIs have become key agents of change in rural areas. They not only facilitate access to basic services like sanitation, education, and drinking water but also foster local leadership and accountability. This article highlights the structure, functions, notable achievements, and ongoing challenges faced by PRIs, while emphasizing their essential role in advancing rural transformation, inclusive growth, and true grassroots empowerment.

Keywords : Panchayati Raj, Rural Governance, Decentralization, Local Self-Government, Development Planning

Introduction

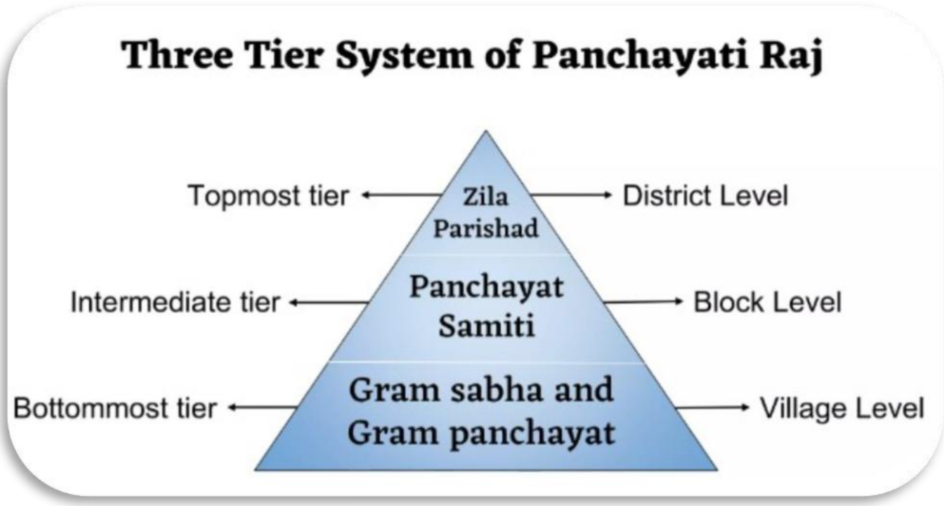
The Panchayati Raj system, constitutionally mandated by the 73rd Amendment Act of 1992, represents a landmark reform in India's democratic and administrative framework. It institutionalized local self-governance, thereby empowering rural communities to participate directly in planning, decision-making, and implementation of development programmes. This constitutional recognition was a step towards realising Mahatma Gandhi's vision of *Gram Swaraj* self-rule at the village level. The essence of the Panchayati Raj system lies in decentralizing administrative authority, thereby enabling villages to address their unique challenges using local knowledge and resources. By doing so, PRIs have not only strengthened democracy at the grassroots but also brought governance closer to the people, especially those in marginalized and underdeveloped regions. Today, these institutions play a vital role in rural development by implementing welfare schemes, managing natural resources, addressing basic needs like education, sanitation, and health, and fostering inclusive and participatory development.

Figure 1: Community Members Participating in a Gram Sabha

Structure of Panchayati Raj

The Panchayati Raj system operates through a **three-tier structure**, ensuring a uniform and integrated mechanism for governance at the village, block, and district levels:

- **Gram Panchayat (Village Level):** The basic unit of local administration, the Gram Panchayat is responsible for managing local affairs, maintaining civic amenities, and implementing government schemes at the village level. It is headed by a *Sarpanch* and supported by elected ward members.
- **Panchayat Samiti (Block Level):** This middle tier coordinates the activities of Gram Panchayats within a block. It serves as a vital link between the grassroots and district administration and is headed by a chairperson elected by the members.
- **Zila Parishad (District Level):** The highest level of the Panchayati Raj system, the Zila Parishad plans and monitors development across blocks within a district. It acts as an advisory and coordinating body for Panchayat Samitis and liaises with state departments for the implementation of various development schemes.



This three-tiered structure ensures representation, decentralization, and inclusivity, with mandated reservations for Scheduled Castes, Scheduled Tribes, and women (minimum 33%, now increased to 50% in several states), thereby promoting equity in local governance.

Roles and Responsibilities

Under the Eleventh Schedule of the Indian Constitution, PRIs have been assigned 29 core subjects that impact rural life and livelihoods. These include agriculture, rural housing, drinking water, education, social welfare, health care, sanitation, and poverty alleviation. The responsibilities of PRIs include:

- **Preparation of Village Development Plans (VDPs):** Identifying local needs and planning activities such as road construction, drinking water supply, school improvement, and health services.
- **Implementation of Central and State Schemes:** Executing flagship programmes like the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), Swachh Bharat Mission (SBM), and Pradhan Mantri Awas Yojana – Gramin (PMAY-G).
- **Resource Management:** Managing community assets like ponds, village roads, grazing lands, and water bodies through community involvement.

- **Mobilizing Community Participation:** Conducting *Gram Sabhas* to ensure transparency, encourage public involvement, and gain consent for developmental decisions.
- **Service Delivery:** Facilitating the operation of local schools, health centres, fair price shops, and other essential services in rural areas.

Through these roles, PRIs bridge the gap between policy-making and implementation and ensure that governance is responsive to the actual needs of rural people.

Achievements of PRIs

Since their formal inception, Panchayati Raj Institutions have achieved several notable milestones:

- **Women Empowerment:** The reservation of seats for women in PRIs has created space for female leadership at the grassroots. Women Sarpanches and ward members have actively participated in decision-making, often bringing attention to issues like maternal health, girls' education, and water scarcity (Ministry of Panchayati Raj, 2023).
- **Enhanced Accountability and Transparency:** Mechanisms like *Gram Sabhas* and *social audits* have encouraged transparency and community monitoring of public expenditures and service delivery.
- **Localized Solutions and Innovations:** PRIs often devise region-specific strategies to address challenges such as water management, waste disposal, and sustainable farming. For example, many Gram Panchayats have initiated rainwater harvesting projects, community toilets, and biogas production using local resources.
- **Effective Implementation of Schemes:** The close proximity of PRIs to rural populations allows for more effective execution of poverty alleviation and development programmes, thereby increasing their outreach and impact.

Challenges Faced by PRIs

Despite their potential and progress, PRIs face a variety of structural, administrative, and socio-political challenges:

- **Limited Financial Autonomy:** Most Panchayats depend heavily on grants from state and central governments. The lack of independent revenue sources like taxes or local fees restricts their ability to execute plans effectively.
- **Inadequate Training and Capacity-Building:** Many elected representatives lack formal education or training in governance, planning, or budgeting, which affects decision-making quality and administrative efficiency.
- **Political Interference and Bureaucratic Control:** State-level political dynamics and bureaucratic oversight often dilute the autonomy of PRIs, reducing their effectiveness as independent institutions.
- **Weak Digital Infrastructure:** In remote rural areas, poor internet connectivity and lack of digital literacy hinder the adoption of e-governance tools, thereby affecting transparency and service delivery.

These challenges, if unaddressed, can compromise the objectives of decentralized development and weaken grassroots democracy.

Conclusion

Panchayati Raj Institutions symbolize the spirit of participatory democracy in India. They reflect the nation’s commitment to empower rural citizens, promote social justice, and ensure need-based, localized governance. By placing decision-making power in the hands of the people, PRIs not only strengthen rural voices but also make development more inclusive, efficient, and sustainable. However, their success depends on continuous support in terms of capacity, finance, autonomy, and political will. Strengthening PRIs is not merely an administrative necessity but a moral imperative to build a more self-reliant, equitable, and prosperous rural India.

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PLANT GROWTH-PROMOTING RHIZOBACTERIA: FOUNDATIONS FOR ENVIRONMENTALLY SUSTAINABLE AGRICULTURE

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Abstract
Plant Growth-Promoting Rhizobacteria (PGPR) comprise a broad spectrum of beneficial microorganisms inhabiting the rhizosphere, where they support plant development through multiple direct and indirect pathways. Their contributions include the synthesis of plant growth regulators, nitrogen fixation, phosphate solubilisation, siderophore production, and suppression of plant pathogens through biocontrol pathways. By boosting crop yields and reducing dependence on synthetic fertilizers and pesticides, PGPR play a pivotal role in advancing sustainable agricultural practices. This article explores the diversity, taxonomic classification, and functional strategies of PGPR, with particular attention to their roles in nutrient uptake, enhancement of stress resilience, and mitigation of plant diseases. As environmentally friendly and economically viable alternatives to conventional agrochemicals, PGPR hold significant promise for integration into contemporary farming systems.

Keywords
Plant Growth-Promoting Rhizobacteria (PGPR), rhizosphere, biofertilizers, sustainable agriculture.

Introduction
The intensification of agricultural production over recent decades has led to an overreliance on chemical inputs, resulting in environmental degradation, soil health decline, and reduced microbial diversity. To address these challenges, sustainable agriculture is gaining global attention. One promising approach within sustainable farming is the application of biofertilizers, particularly Plant Growth-Promoting Rhizobacteria (PGPR). These beneficial microorganisms inhabit the rhizosphere—the biologically active region of soil surrounding plant roots—and enhance plant growth through multifaceted mechanisms.

PGPR improves plant growth by increasing nutrient availability, producing growth regulators, enhancing stress resistance, and providing protection against plant pathogens. Unlike synthetic fertilizers and pesticides, PGPR are environmentally safe and economically viable. Common PGPR genera include *Pseudomonas*, *Bacillus*, *Azospirillum*, *Azotobacter*, *Mesorhizobium*, and *Rhizobium*. This article explores the diversity, classification, and plant-beneficial mechanisms of PGPR in the context of their potential role in sustainable agriculture.

Arrays of PGPR
There are two major arrays of PGPR
a.Symbiotic /intracellular - colonise the interior of plant cells
Eg, Nodule bacteria
b. Free-living /extracellular - exist outside the plant
Eg, *Bacillus, Pseudomonas, Azotobacter*

What are the various pathways through which PGPR enhance plant growth

1.Direct Pathways

Production of Plant Growth Regulators (PGRs)

Plant Growth-Promoting Rhizobacteria (PGPR) synthesize a range of PGRs, including indole-3-acetic acid (IAA), gibberellic acid (GA_3), zeatin, ethylene, and abscisic acid (ABA), which exert a direct influence on plant growth.

Eg : *Pseudomonas, Xanthomonas, Azospirillum, Acetobacter, Rhizobium,* etc, possess the ability to produce phytohormones.

Nutrient Mobilization

Plant Growth-Promoting Rhizobacteria (PGPR) significantly contribute to enhancing nutrient availability in the soil, thereby improving plant access to essential elements. These beneficial microbes transform insoluble forms of key nutrients, such as phosphorus and potassium, into plant-available forms through the secretion of organic acids and specific enzymes. They also release siderophores—iron-binding molecules—that facilitate iron acquisition, particularly under conditions of iron scarcity. Furthermore, certain PGPR strains are capable of fixing atmospheric nitrogen into ammonia, which plants can readily assimilate. By promoting efficient nutrient uptake and reducing dependence on chemical fertilizers, PGPR play a vital role in sustaining plant health and boosting crop productivity.

Nitrogen Fixation

Certain PGPR strains possessing nitrogenase genes have the ability to transform atmospheric nitrogen (N_2) into ammonia (NH_3). This process supplies plants with a usable form of nitrogen, as they are unable to assimilate atmospheric nitrogen directly.

Phosphate Solubilization

Phosphorus is an essential macronutrient for plant growth, yet much of it in the soil occurs in insoluble forms that plants cannot directly absorb. Phosphate-solubilizing PGPR release organic acids such as gluconic and citric acids, which transform these insoluble phosphates into bioavailable forms. This natural process reduce the reliance on phosphate fertilizers. In addition to enhancing phosphorus availability through solubilization, phosphorus biofertilizers improve the efficiency of biological nitrogen fixation and promote the uptake of micronutrients like iron (Fe) and zinc (Zn) by producing various plant growth-enhancing compounds.

E.g., *Bacillus, Beijerinckia*, *Enterobacter*, *Pantoea,* etc.

Siderophore Production

Plant Growth-Promoting Rhizobacteria (PGPR) produce extracellular metabolites known as siderophores—low molecular weight compounds that chelate iron (Fe^{3+}). The presence of such PGPR in the rhizosphere facilitates a more efficient supply of Fe^{3+} to plants, thereby boosting crop growth and yield. Moreover, by binding Fe^{3+}, siderophores reduce its availability to other soil microorganisms, limiting the growth and activity of competing microbes.

2. Indirect Pathways – PGPR as Biocontrol Agents

Plant Growth-Promoting Rhizobacteria function as biocontrol agents by employing one or more of the following pathways.

Production of antibiotics

Antibiotics are low-weight molecular compounds that suppress the development of plant pathogenic microorganisms.

Eg, Phenazine, 2,4-diacetylphloroglucinol (DAPG), oomycin-A, pyoluteorin, pyrrolnitrin, tensin, tropolone, and the cylic lipopeptides synthesis.

These are produced mainly by *Pseudomonas, Bacillus,* etc.

Resource and Habitat Competition

To establish dominance over other soil microorganisms, rhizospheric bacteria must effectively compete for limited nutrients and space. This competitive ability is a key strategy in reducing the occurrence and severity of plant diseases. As a result, rapid and dense colonization of roots by PGPR creates an environment that is unfavorable for the establishment of phytopathogens.

Induced Systemic Resistance (ISR)

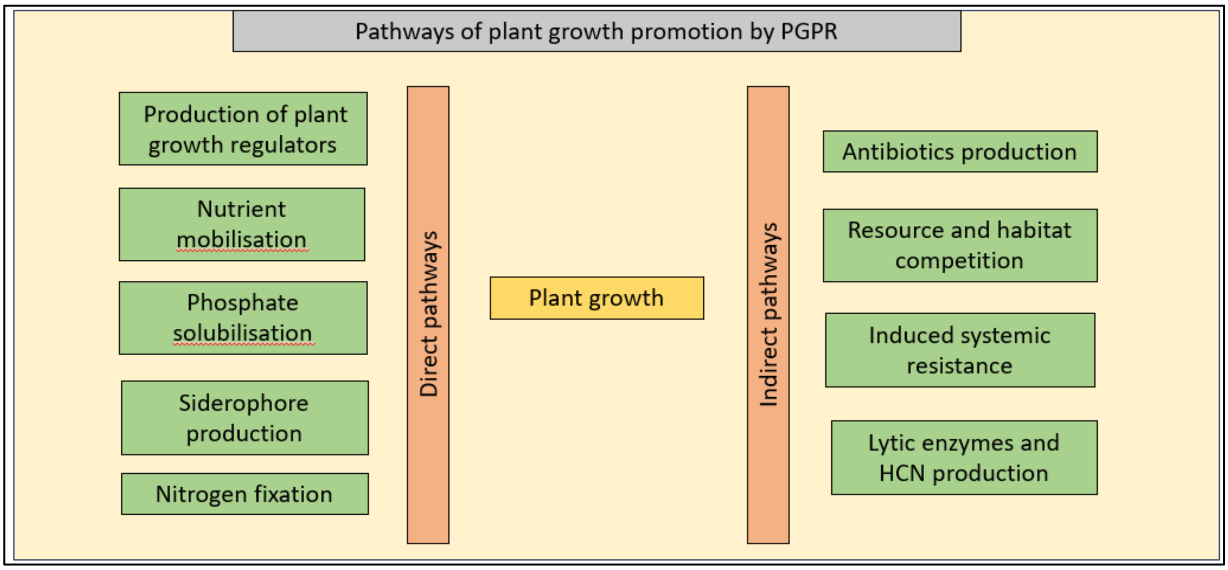
PGPR can trigger a plant's defense system, enabling it to combat pathogenic bacteria, fungi, and viruses. This induced systemic resistance (ISR) operates through signalling pathways involving organic acids and plant hormones such as salicylic acid, jasmonic acid, and ethylene, which activate and enhance the host plant's defense responses against a wide range of pathogens.

Lytic enzymes and HCN production

PGPR produces extracellular enzymes such as chitinases, ß-1-3 glucanases, lipases, cellulases, and proteases, which perform the function of biocontrol. The ability to synthesize anti-fungal metabolites, such as fungal cell wall-lysing enzymes and HCN, suppress the growth of fungal pathogens, and can contribute to the biocontrol action of PGPR.

Conclusion

Plant Growth-Promoting Rhizobacteria (PGPR) are pivotal to advancing sustainable agriculture by stimulating plant growth, enhancing nutrient acquisition, and providing effective protection against phytopathogens. Through a combination of direct and indirect functional pathways, they not only promote crop development but also help reduce dependence on chemical inputs, thereby supporting environmental conservation. Incorporating PGPR into contemporary farming practices offers a viable strategy for achieving higher yields in an eco-friendly manner. However, sustained research, coupled with field-based validation and optimized formulations, is crucial to fully exploit their potential and encourage their large-scale application in sustainable crop production systems.



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PLANT-BASED PROTEINS AS NEXT-GENERATION FUNCTIONAL FOODS

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Abstract
The growing demand for sustainable and health-conscious food choices has led to the rapid rise of plant-based proteins as viable alternatives to animal-derived products. Innovations in food technology, including extrusion, fermentation, and novel fat structuring methods, have significantly enhanced the taste, texture, and nutritional profile of plant-based meat and dairy analogues. These alternatives not only offer potential health benefits such as reduced risk of cardiovascular diseases, diabetes, and obesity but also address critical environmental issues by lowering greenhouse gas emissions and reducing land and water use. Despite their promise, challenges such as the presence of antinutrients, allergenic concerns, and consumer scepticism regarding taste and processing remain. Nevertheless, strategic marketing, continued technological advancements, and consumer education are expected to drive further integration of plant-based proteins into global diets. This paradigm shift supports a broader transition toward ethical and sustainable food systems, aligning with global health and environmental goals.

Key words: Plant-based proteins, sustainable diets, meat alternatives, food technology, consumer perception, nutritional benefits, environmental impact.

Introduction

The growth of plant-based meat and dairy alternatives, such as those produced by companies like Beyond Meat and Impossible Foods, is driven by a combination of consumer demand for sustainable, ethical and health-conscious food options. These products aim to replicate the taste, texture and nutritional profile of animal-based products while offering environmental and health benefits. The development and popularity of these alternatives are supported by advancements in food technology and a growing awareness of the ecological impact of traditional meat and dairy production. These advancements not only enhance sensory attributes but also help in addressing nutritional gaps often found in plant-based analogues compared to their animal counterparts (Pingali *et al.*, 2023). By leveraging these technologies, companies can develop products that more closely meet consumer expectations for both taste and health benefits. The following sections examine the key factors driving the ongoing growth of plant-based proteins.

Technological Advancements

The production of plant-based proteins involves sophisticated technologies such as extrusion, fermentation, and protein interaction techniques to improve texture and flavor, making them more appealing to consumers (Xiao *et al.*, 2023) (Schweiggert-Weisz *et al.*, 2024). Furthermore, understanding consumer preferences and perceptions is crucial for the continued success of plant-based alternatives, as these factors significantly influence purchasing decisions and market trends. Consumer education regarding the benefits and nutritional profiles of plant-based proteins will be essential to further drive acceptance and integration of these alternatives into mainstream diets (Jesus, 2023). As consumers become more informed about the health and environmental advantages of plant-based proteins, their willingness to incorporate these alternatives into their diets is likely to increase.

Innovations in plant-based fats, using emulsions and gels, enhance the sensory attributes of these products, such as appearance and mouthfeel, which are crucial for consumer acceptance (Jung *et al*., 2024). This focus on sensory attributes is vital, as research indicates that perception of taste, texture, and appearance significantly affects consumer acceptance of plant-based alternatives (Imram, 1999). Moreover, effective marketing strategies that highlight these innovations can further boost consumer interest and encourage dietary shifts towards sustainable options (Erfanian *et al*., 2024).

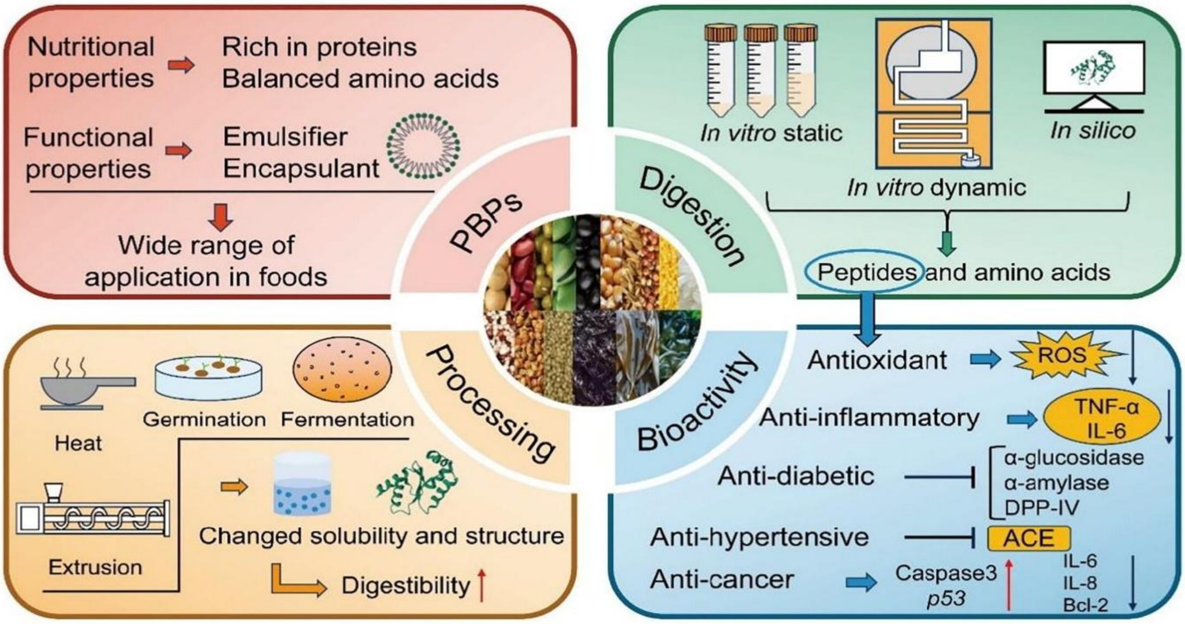

Fig. 1: Plant-based proteins: advances in their sources, digestive profiles *in vitro* and potential health benefits Source: (Li *et al*., 2024)

Nutritional and Health Benefits

Plant-based alternatives are often lower in fat and calories compared to their animal-based counterparts, and they can help regulate blood pressure, diabetes, and cardiovascular disease risk (Singh *et al*., 2024). Incorporating these alternatives into diets can lead to improved health outcomes, particularly in reducing the risk of chronic diseases associated with high meat consumption (Munialo & Andrei, 2023). These health benefits, combined with the ecological advantages of reduced meat consumption, position plant-based diets as a viable option for promoting overall well-being and sustainability.

Despite their benefits, plant-based proteins may contain antinutrients like lectins and phytates, which can affect nutrient absorption. Therefore, ongoing research is needed to optimize their nutritional profile (Schweiggert-Weisz *et al*., 2024). Further exploration of consumer attitudes and perceptions towards these antinutritional factors will be crucial in enhancing the acceptance and integration of plant-based proteins into diets.

Environmental and Ethical Considerations

The production of plant-based proteins requires significantly less land, water, and energy compared to animal-based proteins, reducing deforestation and biodiversity loss (Meat Alternatives, 2022). Moreover, the shift towards plant-based diets is increasingly recognized as a strategy to mitigate climate change and promote sustainable food systems (Munialo & Andrei, 2023) (Chib *et al*., 2024). This transition not only addresses environmental concerns but also aligns with public health goals by reducing the prevalence of diet-related diseases.

These products align with consumer values regarding animal welfare and environmental sustainability, contributing to their growing popularity (Aimutis, 2022). The increasing consumer demand for plant-based alternatives reflects a broader societal shift towards sustainability and ethical consumption, emphasizing the need for continued innovation in this sector.

Market Growth and Consumer Trends

The plant-based sector is rapidly expanding, with a diverse range of products available in supermarkets, reflecting consumer interest in varied and innovative food options (Marchese *et al*., 2024). The convergence of health, environmental, and ethical considerations is driving a significant transformation in food systems, emphasizing the importance of plant-based diets for future sustainability.

Companies like Impossible Foods are capitalizing on this trend by expanding their market presence both domestically and internationally, highlighting the global potential of plant-based alternatives (Rogers, 2023). This transformation is not only beneficial for individual health but also essential for achieving global sustainability goals, as plant-based diets can significantly reduce environmental impacts and improve food security.

Challenges and Future Directions

Despite their growth, plant-based proteins face challenges such as replicating the complex flavors and textures of animal products and addressing potential allergens (Jung *et al*., 2024). To overcome these challenges, ongoing research and development are crucial in improving the formulations and safety profiles of plant-based alternatives, ensuring they meet consumer expectations and dietary needs.

Continued research and development are essential to overcome these challenges and to ensure that plant-based diets meet nutritional needs effectively (Schweiggert-Weisz *et al*., 2024) (Barakat *et al*., 2022). Furthermore, addressing consumer scepticism about taste and processing methods will be essential for the widespread adoption of plant-based alternatives, as these perceptions directly influence purchasing behaviour (Geng, 2024).

Conclusion

The growth of plant-based proteins is promising, it is important to consider the potential limitations and challenges associated with these products. Issues such as nutrient bioavailability, the presence of antinutrients, and the need for further technological advancements to improve sensory attributes remain areas of active research. Additionally, the long-term health impacts of a diet heavily reliant on plant-based alternatives are not yet fully understood, necessitating further studies to ensure these products can sustainably meet human nutritional requirements.

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REVIVING TRADITION: NATURAL FARMING AS THE FUTURE OF SUSTAINABLE AGRICULTURE

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Introduction

Agriculture in India is more than food production—it is a way of life, deeply linked to culture, tradition, and ecology. For centuries, farmers cultivated crops using organic manures, mulching, mixed cropping, and indigenous seed varieties. These practices sustained both people and the planet. However, the **Green Revolution (1960s onwards)** brought in high-yielding varieties, chemical fertilizers, and pesticides, which boosted production but also led to soil degradation, biodiversity loss, water pollution, and rising farmer costs. Today, as climate change, soil exhaustion, and input-intensive farming threaten sustainability, there is renewed interest in **Natural Farming** is an approach that revives traditional methods while aligning with modern scientific understanding of ecology. Natural farming minimizes external chemical inputs and restores the soil's biological activity, making agriculture **resilient, eco-friendly, and farmer-friendly.**

Natural Farming

Natural farming is an **Agro-ecological approach** that relies on locally available resources, minimal external inputs, and biological processes for crop cultivation. It emphasizes:

- Healthy soils with organic matter and microbial activity.
- Crop diversity instead of monoculture.
- Minimal or zero use of synthetic fertilizers and pesticides.
- Integration of livestock and crops.
- Recycling of farm resources (compost, cow dung, crop residues).

Key Principles (based on Subhash Palekar's Zero Budget Natural Farming - ZBNF):

1. **Beejamrit** – seed treatment with cow dung and urine-based formulations.
2. **Jeevamrit** – microbial solution prepared from cow dung, urine, jaggery, and pulse flour for soil fertility.
3. **Mulching** – crop residue or organic cover to conserve soil moisture.
4. **Waaphasa** – maintaining aeration in soil to promote microbial activity.

Scope of Natural Farming

1. **Soil Health Restoration:** Continuous chemical use has reduced soil organic carbon below 0.5% in many regions. Natural farming increases organic matter, improves structure, and enhances nutrient cycling.
2. **Cost Reduction:** By using on-farm resources, farmers reduce expenditure on costly fertilizers and pesticides.
3. **Climate Resilience:** Healthy soils retain more water and withstand drought and floods better.
4. **Food Safety & Nutrition:** Natural produce has lower chemical residues, meeting rising consumer demand for safe food.

5. **Farmer Livelihoods:** With reduced costs and premium markets for organic/natural produce, farmer incomes can increase.

Case Studies

India

- **Andhra Pradesh:** The state launched the **Andhra Pradesh Community-based Natural Farming (APCNF)** program, aiming to scale natural farming to **6 million farmers by 2030**. Farmers report lower costs and better resilience during droughts.
- **Punjab:** Some farmers shifting from intensive rice-wheat cycles to natural farming with pulses and millets to restore soil fertility.
- **ICAR Initiatives:** ICAR's **National Project on Organic Farming (NPOF)** and Krishi Vigyan Kendras (KVKs) are promoting natural and organic inputs through training and demonstrations.

Global

- **Japan:** Masanobu Fukuoka pioneered "Do-Nothing Farming" with natural methods.
- **Africa:** Smallholders adopting agroecology reduce dependence on imported inputs.
- **Europe:** Growing interest in regenerative and natural farming aligned with EU's Green Deal.

Benefits of Natural Farming

1. **Environmental:**
   - Reduces groundwater contamination from nitrates and pesticides.
   - Increases biodiversity of beneficial insects, pollinators, and soil microbes.
   - Enhances carbon sequestration, helping mitigate climate change.
2. **Economic:**
   - Farmers save money by using cow-based formulations and compost.
   - Access to niche organic/natural markets provides premium prices.
3. **Social:**
   - Empowers small and marginal farmers.
   - Encourages community-based farming models and knowledge sharing.
   - Promotes safe, healthy food for consumers.

Future challenges

- **Yield Gap:** In the initial years, yields may dip compared to high-input systems until soil fertility stabilizes.
- **Market Access:** Farmers need reliable markets to sell natural produce at fair prices.
- **Awareness:** Many farmers are still unfamiliar with preparation of bio-inputs like Jeevamrit.
- **Policy Support:** Subsidies still favor chemical fertilizers, creating uneven competition.

The future plans

1. **Policy Shift:** More government incentives for natural farming (as seen in PM's push for chemical-free farming in Union Budget 2022).
2. **Research Support:** ICAR and state agricultural universities should validate natural formulations and integrate traditional wisdom with modern science.
3. **Market Development:** Branding, certification, and direct farmer-consumer linkages for natural produce.
4. **Capacity Building:** Large-scale training through KVKs, Farmer Producer Organizations (FPOs), and NGOs.

5. **Integration with Climate-Smart Agriculture:** Natural farming can complement CSA by reducing emissions and enhancing resilience.

Conclusion

Natural farming is more than a nostalgic return to the past it is a **forward-looking solution** to the crises of modern agriculture. By reviving traditional practices in harmony with nature, farmers can reduce dependency on chemicals, restore soils, and ensure healthy food for all.

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ROLE OF RECIRCULATING AQUACULTURE SYSTEMS (RAS) IN SUSTAINABLE AQUACULTURE DEVELOPMENT

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Abstract

Recirculating Aquaculture Systems (RAS) are innovative, sustainable fish farming technologies designed to recycle and reuse water while maintaining optimal culture conditions. Through mechanical and biological filtration, oxygenation, and continuous monitoring, RAS enables intensive fish production with minimal water use and improved disease control. As aquaculture demand grows to meet global food security needs, RAS offers high productivity per unit area, reduced environmental impacts, and enhanced biosecurity. However, challenges such as high initial investment, energy dependency, and technical expertise requirements limit its widespread adoption. Strengthening cost efficiency, energy innovations, and skilled manpower will be key to making RAS a cornerstone of future aquaculture.

Keywords : Aquaculture, Sustainability, RAS, Production, Employment.

Introduction

Modern tank-based systems called Recirculating Aquaculture Systems (RAS) are made to raise fish with less water exchange. Toxic ammonia is transformed into less dangerous forms through biofiltration, while water quality and clarity are maintained by mechanical and biological filters. Compared to traditional aquaculture, RAS is far more efficient because more than 90% of the water is recycled. These systems improve biosecurity and lower the risk of disease by separating fish from outside contaminants. RAS allows high-density stocking, continuous oxygen supply, and effective removal of wastes such as uneaten feed, feces, and carbon dioxide. With efficient water treatment as their core, RAS promotes sustainable production, healthier fish, and the capacity to meet growing global demand for aquatic food with limited freshwater resources (Roy *et al*., 2025).

Brief overview of global aquaculture trends- Aquaculture is becoming essential to feed a projected global population of 9 billion by 2050. With wild fish stocks overexploited, aquaculture already provides more than half of the world's fish for human consumption. In 2021, aquaculture reached a record 126 million tonnes worth USD 296.5 billion, with China producing the majority. Freshwater finfish dominate production (85%), and the sector has grown at an average of 6.7% annually over three decades. Aquaculture directly employs 20.6 million people (28% women) and will surpass capture fisheries by 2030, accounting for 52% of all aquatic animal production. While salmon and shrimp show high growth, carps contribute the largest volumes worldwide (Sreevidya *et al*., 2025).

Design of RAS

The Recirculating Aquaculture System (RAS) recycles and treats water before returning it to fish tanks, ensuring efficient use and sustainability. Its main components include growing tanks, particulate removal sump, biofilter, oxygen injection with U-tube aeration, and circulation pumps. Thermostats maintain optimal water temperature for specific species, while ozone and UV sterilization reduce organic loads and pathogens. By combining water reuse with controlled environmental conditions, RAS supports sustainable and intensive fish production.

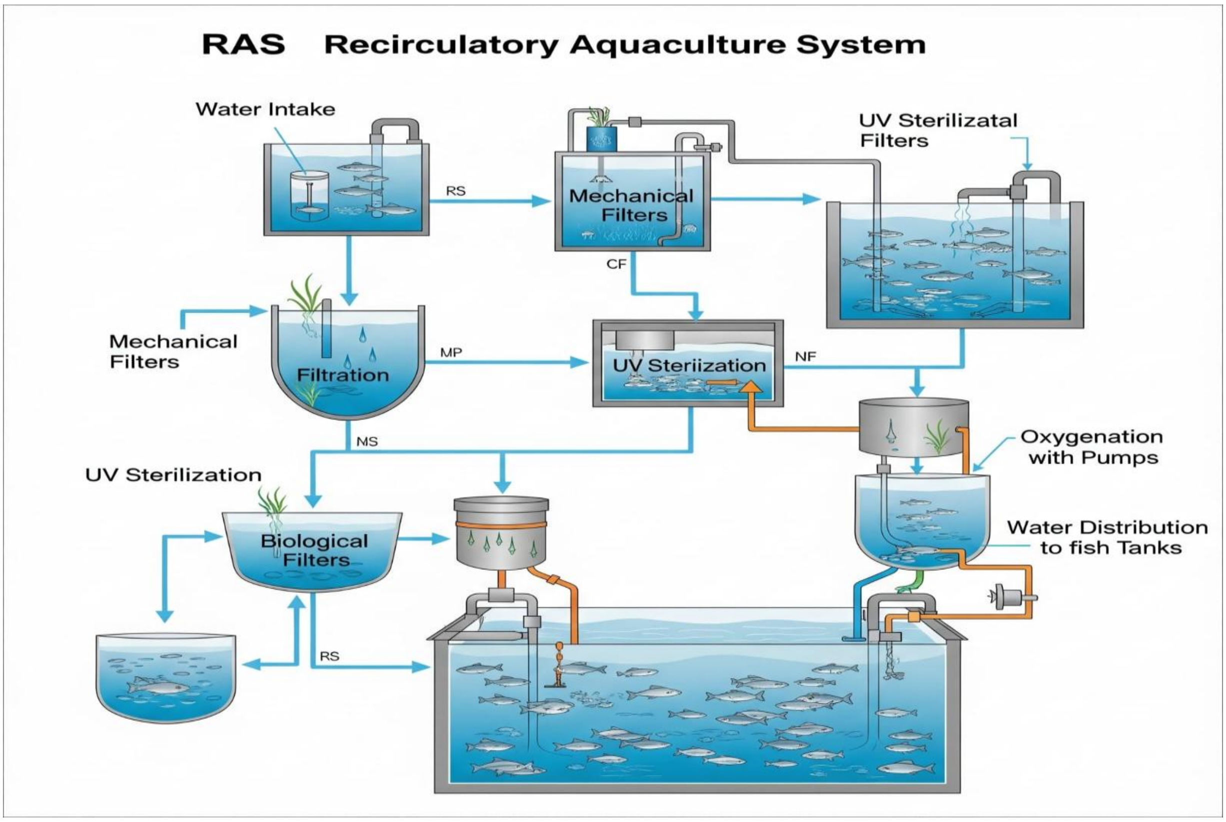

Fig. Morden RAS system

Functional Components of RAS

1. Biofilter (Biological Filtration): Removes harmful ammonia released by fish and converts it into safer forms. Since ammonia toxicity depends on pH and temperature, even slight changes can greatly affect fish health.

2. Mechanical Filter: Captures solid waste and particles using drum filters, micro screens, or alternatives such as disc filters, depth filters, settling tanks, and hydrocyclones, ensuring cleaner water.

3. Solids Removal: Eliminates uneaten feed, feces, algae, and biofilm, which otherwise reduce oxygen and harm fish. Common methods include settling basins, clarifiers, granular media filters, and foam fractionation.

4. Aeration & Oxygenation: Maintains dissolved oxygen at 4–6 mg/L. Aeration is suitable at low densities, while pure oxygenation is required for higher densities using PSA systems, bulk oxygen, or devices like Speece cones and LHOs with up to 90% efficiency.

Monitoring and control

To prevent catastrophic fish losses, it becomes imperative to continuously check oxygen levels, tank levels, and water flow at increasing stocking densities. After an hour of power outages, oxygen levels in moderate systems (60 kg/m³) and high-density systems (120 kg/m³) can drop dangerously in as little as ten minutes. Basic protection is provided by alarm systems connected to automatic oxygen supply valves and phone dialers, while more sophisticated facilities may employ computer-based monitoring with redundancy. A well-equipped laboratory is also necessary to enable routine water-quality tests.

Species suitable for RAS

Common Name	Scientific Name	Notes / Region Suitability
Barramundi / Asian Seabass / Bhetki	Lates calcarifer	Widely cultured in RAS, brackish & marine water
Cobia	Rachycentron canadum	Fast-growing marine species
Silver / Indian Pompano	Trachinotus blochii / Trachinotus mookalee	Suitable for marine RAS
Tilapia	Oreochromis niloticus	Hardy freshwater species, most popular in RAS
Pearl Spot / Karimeen	Etroplus suratensis	Brackish water, high demand in South India
Pangasius	Pangasianodon hypophthalmus	Popular freshwater RAS species
Rainbow Trout	Oncorhynchus mykiss	Best suited for hilly / cold water regions

Advantages

- High water reuse (over 90%) → low water requirement
- Efficient energy and land use for intensive culture
- Provides a controlled environment for fish growth
- Better disease prevention and biosecurity
- Filters out fine particles → maintains high water quality
- Optimal feeding and faster growth rates
- Easy harvesting and grading
- Equipment can be cleaned and reused

Disadvantages

- High capital investment with long payback period
- High energy consumption for continuous operation
- Water loss during backwashing of filters
- Flow rate variations due to filter clogging
- Requires uninterrupted electricity and reliable water supply
- Needs specialized high-quality feed
- Demands skilled technical staff for management

Challenges and future adoption of RAS systems

When asked what obstacles might prevent RAS from being widely adopted in the future, the main response was the financial implications of the system. Businesses reaffirmed this finding, demonstrating that in over 80% of cases, financial performance is subpar and that the return on capital invested is insufficient—that is, it takes an average of more over 8 years to recover the initial investment. Costs per unit of manufacturing capacity and running costs must therefore be decreased. The primary concepts for future development are the creation of new energy sources and the recycling of system byproducts (both of which are mentioned in 85% of the respondents' responses as potential solutions) (Chouhan *et al*., 2025).

Future Prospects in RAS

Climate change, freshwater scarcity, and disease outbreaks threaten the future of aquaculture. With the global population projected to reach 8.5 billion by 2030 and fish consumption expected to rise by 1.8%, farm production faces added pressure as capture fisheries decline (Roy *et al*., 2025). Recirculating Aquaculture Systems (RAS) offer a solution by using minimal water, controlling diseases, and producing 30–50 times more fish per unit area than traditional farming. However, high investment costs and long payback periods (often over eight years) limit adoption. To expand RAS, efforts must focus on reducing production costs, improving energy efficiency, and utilizing byproducts to build a sustainable blue economy.

Conclusion

Recirculating Aquaculture Systems (RAS), which offer controlled culture conditions, increased yields per unit area, and efficient production with less water consumption, are a breakthrough in sustainable fish farming. Aeration, mechanical and biological filtration, and ongoing monitoring are essential components that guarantee the health of the fish and the purity of the water. Long payback periods and hefty capital expenditures, however, continue to be significant obstacles. Innovations in energy efficiency, cost reduction, and supportive legislation will be necessary for greater adoption. RAS has a great potential to safeguard ecosystems and meet future food demands.

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NEW-AGE NURSERY PRACTICE FOR BETTER PLANT GROWTH

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Abstract

Raising strong, healthy plants starts at the nursery level. But the way we've been doing it for decades — with open soil beds, hand watering, and basic tools — doesn't always give us the best results. As the demand for good-quality plants grows, especially in cities and commercial farms, people are turning to newer, smarter ways of raising seedlings. This article looks at the most promising nursery techniques being used today — from plug trays and misting systems to root trainers and tissue culture — and how they're changing the way we grow plants from the ground up.

Introduction

A good plant begins with a good start. Whether it's a fruit tree in an orchard or a tomato plant in a kitchen garden, how it's raised in the nursery makes a big difference in how it performs later. Traditional nurseries, where seeds are sown directly into open soil and cared for manually, often face problems like poor germination, uneven growth, and high disease rates. As farming becomes more technology-driven and space becomes limited — especially in urban areas — growers are looking for ways to get better results with fewer resources. That's where modern nursery techniques come in.

Why These Techniques Matter

New nursery practices aren't just about being high-tech — they're about being smart and efficient. Here's why they're so important:

- Healthier Plants: Plants started in controlled conditions are usually healthier and more uniform.
- Less Wastage: They help save water, space, labor, and other resources.
- Ready for Market: Commercial farms need large numbers of identical, healthy seedlings. These methods deliver exactly that.
- Weather-Proof: With tools like polyhouses and misting systems, seedlings are less affected by heatwaves, heavy rains, or cold snaps.
- Urban Friendly: Space-saving methods are perfect for rooftop and balcony gardens.

Emerging Techniques in Nurseries:

Plug Tray Propagation

Seedlings are grown in small cells within plastic trays, each one with just the right amount of growing media. This keeps roots from getting tangled and makes transplanting super easy — especially for crops like capsicum, cabbage, and tomato.

Using Soilless Media

Instead of regular soil, materials like cocopeat or vermiculite are used. They're clean, light, and great at holding moisture. Plus, they reduce the chances of soil-borne pests and diseases.

Mist Chambers

These are enclosed areas with fine water misters that keep humidity levels high — perfect for encouraging cuttings to develop roots. They're widely used for ornamental plants and fruit crops.

Use of Biodegradable Containers Transitioning to biodegradable pots and trays reduces plastic waste and aligns with sustainable nursery practices.

Tissue Culture Labs
This high-tech method grows new plants from tiny tissue pieces in a lab. It's slow to start but great for mass-producing identical, disease-free plants like banana, strawberry, and orchids.

Root Trainers
These are special containers that guide roots downward and prevent them from circling around the pot. They're often used in forestry nurseries for trees like teak and eucalyptus.

Automated Irrigation & Fertigation
These systems use sensors and timers to deliver the right amount of water and nutrients to each seedling. It's efficient, reduces human error, and saves resources.

Nurseries Under Cover
Structures like shade nets and polyhouses protect young plants from harsh sun, rain, or pests. They also help keep the temperature and humidity stable, which leads to faster and healthier growth.

Smart Nursery Systems and Automation

- **IoT and Machine Learning Integration:**
  Contemporary nursery systems are increasingly incorporating Internet of Things (IoT) technologies paired with machine learning to track and control key environmental parameters like light, temperature, and humidity. This level of automation helps maintain ideal growing conditions for seedlings, promoting healthier development while conserving resources such as water and energy.
- **LED Lighting for Enhanced Growth:**
  Studies have shown that using LED lighting with customized light intensity and wavelength — optimized for plant photosynthesis — can significantly boost seedling growth. In fact, yield improvements of up to 44% have been reported. Moreover, LEDs are energy-efficient, making them an environmentally friendly option for modern nursery operations.

Where These Techniques Are Being Used

- Vegetable & Fruit Production: Farmers use these techniques for crops like tomato, chili, brinjal, papaya, and banana.
- Floriculture: Flower growers rely on mist chambers and soilless media to raise healthy ornamentals.
- Urban Farming: Plug trays and compact grow systems fit well into small balconies or terraces.
- Forestry: Root trainers help prepare tree saplings for large-scale planting.
- Research & Conservation: Tissue culture helps propagate rare or endangered species in labs.

Conclusion
The nursery is where every plant's journey begins, and getting it right can make all the difference. With modern techniques now widely available — and often affordable — growers have more tools than ever to raise healthier, stronger, and more productive plants. These methods are not just about improving yields; they're about making plant production more efficient, sustainable, and suited to today's changing world. As we move forward, embracing these smarter nursery practices will be key to growing greener — and growing better.

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SCOPE OF PRECISION LIVESTOCK FARMING FOR OBTAINING SUSTAINABLE LIVESTOCK PRODUCTION

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Introduction

The global demand for animal products such as meat, milk, and eggs has been increasing steadily due to factors like population growth, rising incomes, and changing dietary patterns (Food and Agriculture Organization [FAO], 2022). Meeting this demand presents significant challenges for traditional livestock farming systems, which often struggle to balance productivity with animal welfare and environmental sustainability. Precision Livestock Farming (PLF) has emerged as a revolutionary approach that leverages advanced technologies to optimize the management of livestock at the individual animal level, enabling farmers to enhance productivity, improve animal health, and reduce environmental impacts.

This article explores the principles, technologies, benefits, challenges, and future prospects of PLF. It also provides an overview of its historical context, real-world applications, socio-economic implications, and policy considerations.

Historical Background: From Traditional to Precision Farming

Historically, livestock farming relied heavily on manual observation and experience-based management. Farmers assessed animal health, nutrition, and breeding performance through periodic visual checks and generalized practices suitable for herds or flocks rather than individual animals. While these methods sustained communities for centuries, they often resulted in inefficiencies such as delayed disease detection, over or under-feeding, and uneven productivity (Berckmans, 2017).

With the rise of digital technologies and sensor innovations in the late 20th century, agriculture began shifting towards precision methods, initially focused on crop farming. Precision Livestock Farming followed suit as a natural progression, integrating real-time data collection, automation, and data analytics to revolutionize animal agriculture. The move towards PLF reflects broader trends in ‘smart farming’ aimed at enhancing resource use efficiency and sustainability in the face of mounting global food security concerns.

What is Precision Livestock Farming?

Precision Livestock Farming refers to the use of modern technology-driven tools and data analytics to monitor and manage livestock at the individual animal level (Berckmans, 2017). Unlike conventional livestock management practices, which treat animals collectively, PLF leverages sensors, automated systems, and machine learning algorithms to continuously track physiological and behavioral parameters of each animal in real time (Rutten *et al*., 2013).

By collecting precise and timely information, PLF enables farmers to make data-driven decisions that optimize production efficiency, promote animal welfare, and minimize environmental footprints (Fournel *et al*., 2021). This individualized approach tailors interventions such as feeding, health care, and breeding to meet the specific needs of each animal, leading to more effective and sustainable livestock management.

Core Principles of Precision Livestock Farming

1. **Continous Monitoring**: PLF systems employ sensors and devices that collect data continuously on physiological parameters like body temperature, heart rate, activity levels, rumination, and feed intake (Fournel *et al*., 2021). Continuous monitoring facilitates early detection of health problems, stress, or behavioral changes, enabling timely interventions and reducing mortality rates.
2. **Individualized management**: Instead of managing animals as groups, PLF emphasizes individualized care that accounts for differences in health, productivity, and behaviour among animals (Berckmans, 2017). This approach improves overall herd or flock health, reduces disease spread, and increases production efficiency.
3. **Data-Driven decision making:** The vast amount of data collected is processed using software platforms and machine learning algorithms to generate actionable insights (Rutten *et al*., 2013). Farmers can optimize nutrition, breeding programs, and health management based on evidence rather than intuition.
4. Automation and Integration: Automated systems for feeding, milking, waste management, and environmental control reduce labor costs and improve consistency. Integration of various technologies into a unified platform streamlines farm operations and enhances decision-making (Fournel *et al*., 2021).

Technologies Driving Precision Livestock Farming

Wearable Sensors: Devices such as smart collars, ear tags, and pedometers measure vital signs and behavioral metrics, providing real-time alerts about potential illnesses or heat stress (Neethirajan, 2020).

Automated Milking Systems: Robotic milking machines improve milking efficiency while continuously assessing milk quality and udder health, leading to enhanced productivity (Rutten *et al*., 2013).

Environmental Sensors: Monitoring barn temperature, humidity, ammonia levels, and ventilation helps maintain optimal environmental conditions crucial for animal comfort and productivity (Fournel *et al*., 2021).

Data Analysis and Machine Learning: Software platforms analyze sensor data, predict health issues, and optimize farm management decisions using AI algorithms (Neethirajan, 2020).

Benefits of Precision Livestock Farming

1. **Enhanced Animal Health and Welfare**: Continuous monitoring enables early disease detection, reducing the spread of infections and veterinary costs (Berckmans, 2017). Personalized care minimizes animal stress, improving overall welfare.

2. **Increased Productivity**: Optimized feeding, breeding, and health management enhance growth rates, milk yields, and reproductive performance (Rutten *et al*., 2013). Automation reduces human error and labor requirements.
3. **Resource Efficiency and Environmental Sustainability**: Precise use of feed, water, and medications reduces waste, lowering environmental footprints through decreased greenhouse gas emissions and nutrient runoff (Fournel *et al*., 2021). Better manure management further reduces pollution risks.
4. **Economic Benefits**: Although initial investment costs are high, PLF can increase farm profitability by lowering labor and veterinary expenses while improving yields (Neethirajan, 2020). Real-time data empowers farmers to manage risks proactively.

Environmental impact of PLF: Towards Climate-Smart Agriculture

Livestock farming contributes substantially to greenhouse gas emissions, land degradation, and water use globally. PLF offers pathways to mitigate these impacts by improving feed conversion efficiency and reducing waste (FAO, 2022). For instance, early disease detection means fewer animals die prematurely, reducing the overall resource burden. Optimized feeding limits overuse of feed and excess nitrogen excretion, cutting methane and nitrous oxide emissions. Environmental sensors facilitate precise climate control within barns, improving animal comfort while lowering energy consumption. Manure management automation reduces nutrient leaching into water bodies. Collectively, these improvements contribute to climate-smart livestock systems aligned with sustainability goals.

Socio-economic implications and case studies

PLF has transformative potential for rural livelihoods but also poses challenges. For large-scale commercial farms, automation and data-driven management improve competitiveness and economic viability. For smallholder and resource-poor farmers, high costs and technical demands present barriers.

However, innovative models are emerging. In countries like the Netherlands and Denmark, dairy farms use robotic milking and sensor systems to boost efficiency and animal welfare (Rutten *et al*., 2013). In India, pilot projects deploying wearable sensors in village herds show promise in early disease detection and productivity improvement, helping small farmers gain access to veterinary services (Vikaspedia).

The adoption of PLF also affects labour patterns, potentially reducing manual jobs but creating demand for skilled technicians and data analysts. Gender dynamics in farming communities may shift as women engage with technology-driven roles, contributing to empowerment.

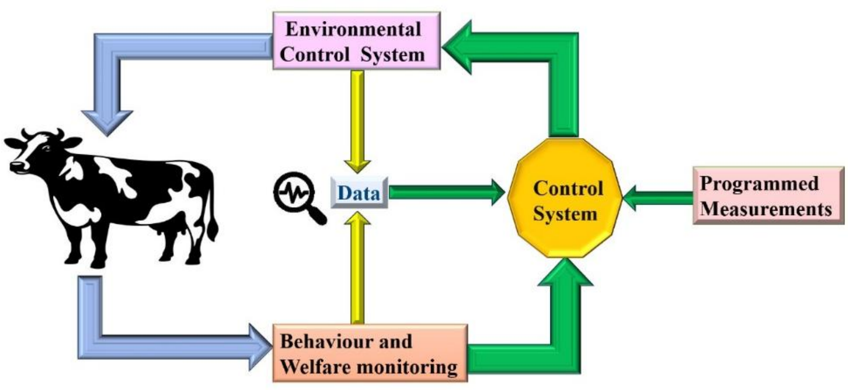

Fig:- Flow chart of Precision livestock Farming

Challenges in implementing Precision Livestock Farming

1. **High Initial Cost and Accessibility**: PLF technologies require significant upfront investments, often out of reach for small-scale farmers (Rutten *et al*., 2013). Subsidies and low-cost solutions are needed.
2. **Technical Expertise and Training**: Effective use demands knowledge in technology operation and data interpretation. Capacity-building programs are essential to bridge skills gaps (Berckmans, 2017).
3. **Infrastructure Limitations**: Reliable internet connectivity and power supply are critical for real-time data transmission, posing challenges in remote and underdeveloped regions (Neethirajan, 2020).
4. **Data Privacy and Security**: Vast data collection raises concerns about ownership, misuse, and cyber-security. Clear governance frameworks are required (Fournel *et al*., 2021).
5. **Integration with Traditional Practices**: Adapting existing farming systems to incorporate PLF requires infrastructure changes and cultural shifts, which may face resistance (Rutten *et al*., 2013).

Future Prospects

The future of PLF looks promising with ongoing innovations:

- **Emerging Technologies** such as blockchain for supply chain transparency, drones for herd monitoring, and advanced AI for predictive health management will enhance PLF capabilities.
- **Research and Development** focused on affordable, user-friendly tools tailored to diverse farm sizes and regions will support wider adoption.
- **Policy Support** through financial incentives, rural infrastructure development, and data privacy regulations will be crucial.
- **Training and Extension Services** must be scaled up to build farmers' technical skills and confidence.
- **Collaborative Efforts** among governments, technology providers, researchers, and farmers are needed to overcome barriers and maximize PLF benefits.

Conclusion

Precision Livestock Farming represents a paradigm shift in livestock farming, leveraging technology to enhance productivity, animal welfare, and environmental sustainability. By enabling continuous, individualized monitoring and data-driven management, PLF offers solutions to meet the rising global demand for animal products in a more ethical and efficient manner. While challenges related to cost, expertise, infrastructure, and data security exist, coordinated efforts across multiple stakeholders can help overcome these hurdles. As PLF continues to evolve with technological advancements, it holds the promise of transforming livestock farming into a smarter, more sustainable sector that supports food security and rural development worldwide.

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THE ROLE OF SUGAR SIGNALING IN PLANT IMMUNITY

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Abstract

The field of plant immunity is undergoing a significant paradigm shift, moving from a traditional genetic perspective to one focused on metabolic regulation. This article highlights the revolutionary concept of "sweet immunity," where plant sugars once considered only as fuel are now recognized as dynamic signaling molecules that actively regulate defense mechanisms. This article summarizes the idea of molecular functions of sugar-sensing enzymes like hexokinase and the role of sugar transporters in the metabolic arms race against pathogens. We also discusses the practical agricultural applications of this knowledge, including "sweet priming" and targeted crop breeding, as a sustainable alternative to chemical fungicides. Ultimately, the article advocates for a multi-disciplinary approach to harness this intricate plant-sugar-pathogen relationship to enhance crop resilience and secure global food production.

Introduction

Global food security is increasingly threatened by plant pathogens, which cause significant crop losses and necessitate widespread use of chemical fungicides. While these traditional measures offer a degree of protection, their environmental impact and the evolution of pathogen resistance underscore the urgent need for innovative, sustainable defense strategies. Historically, the scientific community has viewed plant immunity through a genetic lens, and plant sugars were primarily considered a passive energy source. However, a revolutionary new field of research is revealing a far more complex role. Sugars, long seen as mere fuel, are now recognized as a dynamic signaling currency, acting as master regulators of a plant’s immune system (Bolouri Moghaddam and Van den Ende, 2013; Van den Ende et al., 2020). This paradigm shift, often referred to as "sweet immunity," reveals a hidden layer of complexity where a plant’s nutritional and metabolic state is inextricably linked to its ability to mount a robust defense against pathogens (Yamada and Mine, 2024). This novel understanding holds immense promise for developing sophisticated, proactive strategies to enhance crop resilience and secure the global food supply by empowering the plant's own internal defense mechanisms.

Historical Context and Paradigm Shift

The historical trajectory of plant immunity research has undergone a significant shift, moving from a focus on static, recognition-based defenses to a more holistic view of metabolic-driven resistance. Historically, the plant-pathogen interaction was primarily viewed through a genetic lens, centered on whether a plant possessed the necessary resistance (R) gene to recognize a pathogen's avirulence (Avr) factor. While this perspective was groundbreaking, it often led to the marginalization of the broader physiological and metabolic shifts that underpin an immune response. The metabolic status of the plant, particularly its carbon and sugar economy, was conventionally considered a secondary consequence of infection rather than a primary driver of defense. Early observations confirmed that infected tissues often became nutrient "sinks," yet the regulatory significance of this phenomenon was largely unappreciated. However, the advent of modern molecular biology and metabolomics has enabled scientists to analyze these processes with greater precision. This has revealed that sugars and their metabolic derivatives are not merely passive bystanders but are, in fact, active participants in the signaling cascades that regulate immunity (Lastdrager et al., 2014).

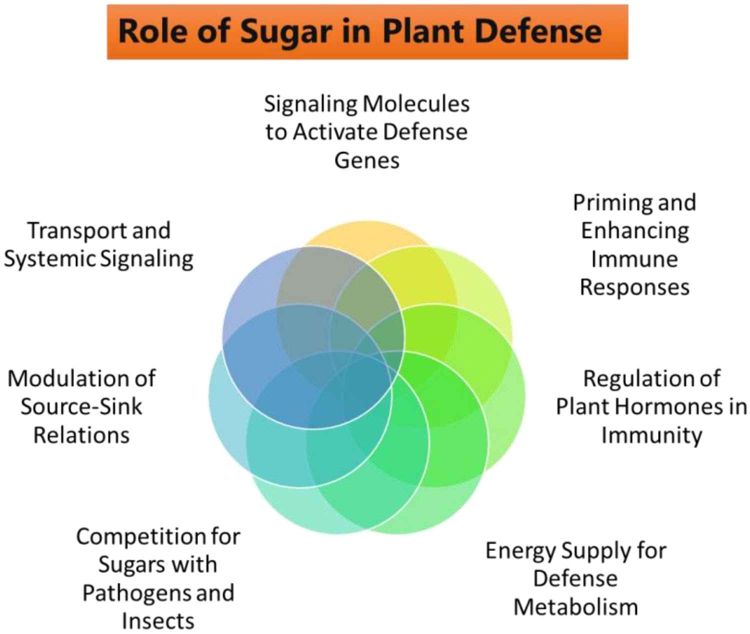

Fig. 1. Multi-faceted Role of sugar in Plant Defense

Molecular Mechanisms of Sugar Signaling

Central to plant sugar signaling is the hexokinase (HXK) family of enzymes, which functions as a dual-purpose metabolic enzyme and a pivotal sugar sensor. While hexokinases are conventionally known for phosphorylating glucose to glucose-6-phosphate, they also possess a non-catalytic signaling function. This dual functionality enables the plant to directly couple its metabolic state to gene expression, growth, and defense responses (Cho et al., 2006). For example, elevated sugar concentrations can trigger hexokinase-mediated regulation of genes involved in both photosynthesis and defense. This mechanism is particularly crucial during infection, as a pathogen's attempt to acquire host sugars serves as a metabolic signal of a threat. In response to this altered metabolic state, the plant can activate defense pathways to counteract the invader (Espinosa-Ruiz et al., 2021).

In addition to their role in sensing, sugar transporters are also integral to immunity. Sugars are actively transported by various sugar transporters (e.g., SWEETs and SUTs) across cellular membranes to supply different plant tissues, including the site of infection. Pathogens frequently engage in a metabolic arms race with the host, attempting to co-opt these transporters for nutrient acquisition. In a counter-strategy, plants have evolved sophisticated mechanisms to modulate the expression and subcellular localization of these transporters, thereby "starving" the pathogen by restricting its access to sugars (Chen, 2014). This intricate and dynamic regulation of sugar sensing and transport represents a fundamental aspect of the metabolic-driven defense response, illustrating the precise resource management plants employ to combat pathogens and ensure survival.

Table1: Key Sugar-Mediated Defense Functions and Associated Genes

Sugar/Compound	Function	Example Defense Genes	Reference
Sucrose	Activates PR genes, anthocyanin accumulation	PR1a, PR1b, NtACS1	Solfanelli et al., 2006; Kim et al., 2008; Bolouri Moghaddam et al., 2012
Trehalose	Induces resistance against powdery mildew, aphids	PR genes	Reignault et al., 2001; Singh et al., 2011; Bolouri Moghaddam et al., 2012
Raffinose, galactinol	Transportable stress signals, activate defense genes	PR1a, PR1b	Kim et al., 2008; Hofmann et al., 2010; Bolouri Moghaddam et al., 2012
Benzoxazinoid-bound sugars	Detoxification and activation of chemical plant defenses (and pest counter-strategies)		Max Planck Institute for Chemical Ecology, 2014

Practical Applications in Agriculture

The profound understanding of sugar signaling's role in plant immunity opens a new frontier for sustainable agriculture. By moving beyond a purely reactive approach to disease, we can proactively fortify crops from within. A key strategy is "**sweet priming**," which involves the application of specific oligosaccharides or sugar analogs to the plant. This process harmlessly mimics an early stage of infection, activating the plant's defense system and preparing it to mount a swift and robust response when a genuine threat emerges (Van den Ende et al., 2020). This method offers a promising, eco-friendly alternative to conventional fungicides, reducing chemical usage and its associated environmental impact. Furthermore, a deeper comprehension of sugar-sensing pathways and sugar transporters enables targeted crop breeding and genetic engineering. Scientists can now select for crop varieties with more efficient sugar management systems. This not only makes them more resilient to pathogens by restricting pathogen access to nutrients (Chen, 2014) and activating a stronger immune response but also ensures that the plant's metabolic resources are optimally directed toward growth and yield. By balancing the dual needs of defense and development, sugar signaling becomes a powerful tool to enhance both crop protection and productivity, thereby securing future food systems (Hanson and Smeekens, 2006).

Future Research and an Integrated Approach

The neglect of this topic in earlier research was, in part, due to the limited technological tools available to study real-time metabolic fluxes. Early plant pathology was focused on visible symptoms and genetic markers. The molecular mechanisms underlying the rapid and dynamic changes in sugar transport and metabolism during an infection were simply too complex to unravel without modern techniques like mass spectrometry and transcriptomics. Consequently, the field remained largely compartmentalized, with geneticists and pathologists working separately from plant physiologists and biochemists. The future of this field, therefore, lies in an integrated, multi-disciplinary approach.

Further research must focus on identifying the specific sugar sensors and their downstream targets, elucidating the cross-talk between sugar signaling and other hormonal pathways, and, most importantly, translating this knowledge into tangible agricultural applications. The ultimate goal is to move beyond a simple defensive posture and empower plants to mount a swift, efficient, and metabolically-informed immune response, ensuring the resilience and productivity of our food systems for generations to come.

Conclusion

The field of plant immunity is undergoing a revolution, one that is as sweet as it is profound. By shifting our perspective from fighting disease with external chemicals to empowering a plant's own internal defenses, we are opening the door to a more sustainable, resilient, and productive agricultural future. The intricate dance between plants, sugars, and pathogens is more than a biological curiosity it is a critical pathway to feeding a growing world.

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GLOBAL AND NATIONAL DYNAMICS OF TOBACCO: POLICY REFORMS, MARKET TRENDS AND CHALLENGES

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Abstract
The tobacco sector continues to occupy a pivotal space at the intersection of agriculture, trade, public health and regulation. This article examines recent developments in India's tobacco industry while situating them within global trends. In India, key policy reforms such as extending the validity of grower registrations and barn licenses from one to three years and permitting the auction of excess Flue Cured Virginia (FCV) tobacco without penalties, reflect the government's commitment to farmer welfare and ease of doing business. On the trade front, India's plantation crop exports surged to $9.16 billion in FY2024-25, with tobacco emerging as a leading performer, recording nearly $2 billion in export earnings. However, experts caution against overproduction, highlighting the need for disciplined adherence to Tobacco Board targets to sustain price stability. At the same time, illicit cigarette trade remains a major domestic concern, as evidenced by recent seizures in Andhra Pradesh, underlining the necessity for stricter enforcement mechanisms. Globally, tobacco continues to drive export growth in countries like Tanzania and Zimbabwe, while the European Union grapples with taxation policies and their unintended consequences on black markets. Additionally, Hong Kong's crackdown on counterfeit goods illustrates the broader networks associated with illicit trade. Collectively, these developments underscore the dual nature of the tobacco economy: as a vital contributor to farmer livelihoods and foreign exchange earnings, yet one fraught with regulatory, health, and smuggling-related challenges. The future of the industry hinges on achieving a delicate balance between supporting producers, maintaining export competitiveness, ensuring compliance, and addressing public health imperatives.

Keywords: Tobacco exports, Farmer welfare, Illicit trade, Policy reforms, Global tobacco markets

Introduction

The tobacco sector continues to be at the intersection of agricultural livelihood, trade expansion, public health concerns and regulatory oversight. Recent developments in India and across the globe illustrate the sector's economic importance as well as the challenges it faces in balancing farmer welfare, trade interests, regulatory enforcement, and illicit trade control. This article provides a comprehensive overview of recent policy reforms, export performance, market opportunities, and regulatory actions in the tobacco industry, with special focus on India while situating the developments within global trends.

Policy Relief for Tobacco Farmers in India

In a major relief for India's Virginia tobacco growers, the Government of India recently notified a significant change in the Tobacco Board Rules, 1976. Traditionally, growers and barn operators were required to renew their certificates of registration and licenses annually. This system created an administrative burden for farmers who already face numerous challenges in cultivation and marketing. The Ministry of Commerce and Industry has now amended relevant sub-rules under Rule 33 and Rule 34N of the 1976 Rules, extending the validity of these documents from one year to three years.

This reform is a part of the government's broader initiative on 'ease of doing business' in agriculture. By reducing the frequency of mandatory renewals, the policy not only saves time and effort for growers but also lowers transaction costs. Farmers can now focus more on cultivation and quality improvement instead of spending resources on annual paperwork. The amendment, published in the Gazette of India, reflects the government's intent to streamline agricultural licensing and align regulations with farmer welfare.

Surge in Plantation Crop Exports: Tobacco Leads the Way

India's plantation sector witnessed remarkable growth in exports during FY2024-25, with commodities such as spices, coffee, tobacco, and tea achieving a combined export value of $9.16 billion. This represents a 17.1% increase from the previous year's $7.82 billion. Among these crops, tobacco emerged as a star performer, registering an impressive 36.6% rise in export earnings. Shipments reached $1.98 billion, up from $1.45 billion in the previous fiscal year.

For much of the last decade, India's tobacco exports fluctuated between $880 million and $980 million, reflecting stagnation. However, the past two years have shown a significant breakthrough. Exports crossed the $1 billion mark in 2022-23 and have now touched nearly $2 billion, underlining a robust growth trajectory. A deeper look reveals that raw tobacco exports contributed significantly, rising from $822 million in 2022-23 to $1.05 billion in 2023-24. On the other hand, exports of manufactured tobacco products, such as cigarettes, showed only marginal growth, moving from $391 million to $397 million.

This surge highlights India's competitive position in the global tobacco market, especially at a time when demand fluctuations in other producing countries created opportunities. It also emphasizes the strategic role of tobacco in India's agri-export basket, where it contributes substantially to foreign exchange earnings.

Need for Discipline Among Tobacco Growers

While Indian growers have benefitted from favourable export prices in recent years, the Chairman of the Tobacco Board of India, Yaswanth Kumar Chidipothu, cautioned against overproduction and unrealistic expectations. Speaking about the ongoing positive market conditions, he reminded farmers that the recent high prices were largely a result of reduced global supply due to adverse weather in key producing countries such as Brazil, Zimbabwe, and Indonesia. This shortage was a temporary phenomenon, and Indian growers should not assume that similar prices will prevail indefinitely.

The importance of adhering to the production targets set by the Tobacco Board was strongly emphasized. These targets are based on extensive market research and help maintain a balance between demand and supply. If farmers exceed the prescribed limits, the resulting surplus could depress prices, harming their own incomes in the long run. He emphasized that only a disciplined, research-backed approach to production planning could ensure sustainable earnings for growers while preserving India's competitiveness in global markets.

Curbing Illegal Cigarette Trade in India

Parallel to the growth in legal tobacco exports, India continues to struggle with illegal trade in cigarettes. In April 2025, vigilance officials in Andhra Pradesh uncovered a large-scale smuggling racket in Vizianagaram district. Acting on intelligence inputs, enforcement teams seized 3.15 lakh cartons of illegal cigarettes valued at approximately Rs. 1.72 crore from a godown in Denkada mandal.

The smuggling operation involved transporting cartons disguised as matchboxes, thereby evading taxation. Officials revealed that the consignment, reportedly from Bihar, was moved to Andhra Pradesh for large-scale illegal distribution. This bust underscores the persistent challenge of illicit tobacco trade in India, which not only results in revenue loss for the government but also undermines public health policies by making cheaper, unregulated cigarettes easily available.

The incident highlights the need for stronger vigilance, better coordination among enforcement agencies, and stricter penalties to deter such activities. With rising taxes on cigarettes, the incentive for smuggling remains high, making it essential for authorities to adopt innovative monitoring systems and technology-driven enforcement.

Government Support to Karnataka's FCV Tobacco Farmers

In another farmer-friendly measure, the central government allowed Flue Cured Virginia (FCV) tobacco growers in Karnataka to sell their excess and unauthorized produce in Board auctions without paying additional charges. This decision was particularly timely, as heavy rains and cyclonic conditions had damaged crops in both Karnataka and Andhra Pradesh, leaving farmers with unexpected yields outside their authorized limits.

The move benefits nearly 70,000 FCV tobacco farmers in Karnataka alone. It not only provides financial relief to growers affected by weather shocks but also ensures that their produce enters the legal auction system instead of being diverted into informal markets. By waiving penalties on excess produce, the government has reaffirmed its commitment to supporting the livelihoods of farmers who form the backbone of India's tobacco economy.

Global Tobacco Developments

Hong Kong: Seizure of Counterfeit Goods and Illicit Cigarettes

Globally, illicit cigarette trade continues to pose significant challenges. Hong Kong Customs recently intercepted a consignment of counterfeit goods and illicit cigarettes at the Hong Kong-Zhuhai-Macao Bridge. The seized items, including around 10,000 illicit cigarettes along with counterfeit luxury goods, were valued at HK$1.3 million. This incident demonstrates how illicit tobacco trade is often linked with broader smuggling networks involving counterfeit consumer goods.

Tanzania: Export Growth Boosted by Tobacco and Cashew

In Africa, Tanzania reported a dramatic 60% increase in traditional export earnings, driven primarily by tobacco and cashew nut exports. According to the Bank of Tanzania, foreign exchange earnings from traditional exports rose from $1 billion to $1.6 billion within a year, with tobacco and cashew contributing $1.2 billion or 80% of the total. The Tanzanian government has set a target of producing 200,000 metric tons of tobacco for the 2024/25 season, underscoring the crop's growing role in the national economy.

European Union: Debate Over Tobacco Tax Policy

In Europe, the policy debate around tobacco taxation remains contentious. The European Union has proposed raising excise duties on tobacco and nicotine products as a strategy to reduce smoking. While the intention is to promote public health, critics argue that blanket tax hikes may backfire. Experiences in France and the Netherlands have shown that higher taxes often fuel black markets, making illicit cigarettes more attractive to consumers. Analysts recommend that the EU focus on stronger law enforcement and border control measures rather than over-reliance on taxation as a deterrent.

Zimbabwe: Progress Towards $5 Billion Tobacco Industry Goal

Zimbabwe has been implementing its Tobacco Value Chain Transformation Plan (TVCTP) since 2021, aiming to create a $5 billion tobacco industry by 2025. Despite a temporary setback in 2024 due to drought, the country has made considerable progress. Production nearly touched 300 million kg in 2023, and the government remains optimistic about meeting its targets in the current season. The plan emphasizes increased production, value addition, localized financing, and diversification to ensure environmental sustainability.

Conclusion: Balancing Opportunities and Challenges

The developments in India and globally highlight the complex dynamics of the tobacco sector. For India, policy reforms such as extending grower registration validity and permitting the sale of unauthorized produce demonstrate responsiveness to farmer needs. Export growth reflects the sector's potential to contribute significantly to national income. However, issues like smuggling and overproduction risks call for vigilance, discipline, and balanced regulation.

Globally, countries like Tanzania and Zimbabwe are leveraging tobacco as a key foreign exchange earner, while regions like the EU grapple with public health imperatives and unintended consequences of tax policies. Hong Kong's seizures remind us of the persistent challenge of illicit trade that transcends borders.

Moving forward, the tobacco industry will require a careful balance between supporting farmer livelihoods, ensuring regulatory compliance, expanding exports, and addressing health concerns. Policy frameworks must therefore remain adaptive, grounded in market realities, and cognizant of the socio-economic importance of the crop.

The global and national dynamics of tobacco present both opportunities and challenges for India. On one hand, tobacco contributes significantly to export earnings, rural employment, and farmer livelihoods. On the other, rising health concerns, policy reforms, and shifting global market preferences demand a more balanced approach. India must navigate these dynamics by promoting sustainable cultivation practices, diversifying farmer income sources, and aligning with international health commitments. A carefully crafted strategy can ensure economic benefits while addressing public health priorities.

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FOOD AND FEEDING HABITS AND REPRODUCTIVE BIOLOGY OF *Cabdio morar* (HAMILTON, 1822)

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Introduction

The *Cabdio morar* is a freshwater fish that belongs to the family Cyprinidae. It is commonly known as morari in Bangladesh (Froese and Pauly 2015), and the previous names of the *Aspidoparia jaya* & *Aspidoparia morar*. This fish is found in moderate to fast-flowing water of rivers, streams, canals, plains and mountainous regions. Globally, it is a Near Threatened species in the IUCN Red List, although recently it has been of least concern in Bangladesh. This fish prefers clear, oxygen-rich waters with sandy or muddy bottoms. C. morar is distributed in the Ganges-Brahmaputra River system of India, Bangladesh, Iran, Myanmar, Nepal, Pakistan and Thailand (Talwar and Jhingran 1991). The morari is the dominant species in the Jamuna River (Bangladesh). Cabdio morar is a major source of animal protein and micronutrients in the diet of rural small-scale farmers (Ross *et al*., 2003; Hossain *et al*., 2009). Cabdio morar is extensively used in ornamental fish (Chaudhry 2010).

Food and Feeding Habits

Cabdio morar is an Omnivorous feed on both phytoplankton and zooplankton (Malhotra and Munshi 1985). However, primarily feeds on phytoplankton, with dominant food items being green algae (Scenedesmus, Pediastrum), euglenozoan, diatoms (Navicula, Nitzschia), Cyanobacteria, zooplankton (Rotifera, Crustacea), small insects, detritus, and organic debris. Its feeding behaviour typically occurs at midwater and bottom surfaces while foraging along the substrate.

Reproductive Pattern

Two breeding seasons have been observed in one year. One breeding season was observed during the monsoon season from May to August, and another during the winter season from December to late January. Seven stages of the ovarian cycle are observed based on histological observation of the female ovary (Table 1). Ovaries can be divided into four phases based on the ovarian developmental stages: (1) Immature, (2) Maturing, (3) Mature and (4) Spent.

Table 1: Ovarian cycle of the ovary of *C. morar*

Sr. No.	Ovarian stages
1	Chromatin nucleolar stage
2	Early Perinucleolar stage
3	Late Perinucleolar stage
4	Yolk vesicle stage
5	Early yolk granule stage
6	Late yolk granule stage
7	Spent stage

Spawning mainly takes place in the shallow areas of rivers and floodplains, where external fertilization occurs. The eggs, which are non-adhesive and creamy in colour, float freely in the water column before eventually settling on the bottom among vegetation. There is no parental care observed during the post-spawning period.

Fig: *Cabdio morar*

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MSP AS A LEGAL RIGHT: BOON FOR FARMERS OR BURDEN FOR THE NATION?

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Abstract

Deep-rooted worries about price volatility and income insecurity in Indian agriculture are reflected in the push to legitimize the Minimum Support Price (MSP). The government points to financial, practical, and legal obstacles, but farmers see legal MSP as a weapon for stability and economic justice. This article investigates the viability of legalizing MSP by looking at its formula, the goals of farmers, and structural limitations. Additionally, it talks about workable substitutes such decentralized procurement strategies, direct income support, and Price Deficiency. The analysis comes to the conclusion that attaining a fair, sustainable, and guaranteed income for India's farming community requires a dynamic policy mix rather than a legally obligatory MSP.

Keywords: Agriculture, Income Support, Payments, Price Volatility, Procurement

Introduction

In recent years, there has been a growing push to legalize Minimum Support Price (MSP). India's farmers, particularly those in Punjab, Haryana, and western Uttar Pradesh, have been calling for legislation that will ensure they may sell their produce at or above the government-announced MSP. Though it has political weight and emotional appeal, is the proposal economically viable? Can farmers in India really be empowered by legal MSP? Or will the state and markets be burdened in ways that cannot be sustained? This article examines Indian agriculture's different routes to income certainty, legal ramifications, government concerns, and farmer aspirations.

What is MSP

As a safety net for farmers, the Minimum Support Price (MSP) is a benchmark price set by the government that guarantees farmers a minimum income for their crops even in the event that market prices fall. The MSP system, which was first implemented in 1965 with the formation of the Agricultural Prices Commission (APC), now known as the Commission for Agricultural Costs and Prices (CACP), was intended to safeguard national food security and farmers' livelihoods by providing a buffer against market volatility (CACP, n.d.). For 23 major crops, including seven cereal crops (paddy, wheat, maize, barley, jowar, bajra, and ragi), five pulses (Arhar, urad, moong, masoor, and gram), seven oilseeds (groundnut, sunflower, soybean, mustard, sesame, niger seed, and safflower), and four commercial crops (cotton, sugarcane (FRP), jute, and copra), MSP is currently announced prior to the sowing season. Additionally, MSP is fixed for Toria (based on mustard) and de-husked coconut (based on copra) as supplementary references (CACP, n.d.).

How it is calculated

Based on a thorough examination of production costs in various states, the CACP calculates MSP. It divides expenses into three groups. They're

- A_2: Provides coverage for all paid-out costs incurred by the farmer, such as diesel, irrigation, leased land rent, hired labor, seeds, fertilizer and pesticides etc.
- A_2 + FL: Increases A_2 by the imputed value of unpaid family labor, which represents the work that family members put into farming.
- C_2: A more thorough cost measure, C_2 comprises A_2 + FL in addition to the interest on owned capital assets and imputed rent on owned land proposed by M.S. Swaminathan (NCF, 2004).

The government typically sets MSP at 1.5 times the A_2 + FL cost, which serves as the foundation for the official Cost of Production (CoP) for the majority of crops, even though many farmers and experts urge MSP based on C_2 (PIB, 2020).

What Farmers Want: Security, Not Sympathy

Agriculture is no longer profitable for millions of Indian farmers. Anger and disillusionment have been fuelled by frequent price crashes, such as the ₹1 per kg onion or the distress sales of tomatoes and pulses. Legalization of MSP is seen by farmers as a means of ensuring fair and consistent prices for their labor-intensive produce. Their demands are rooted in:

- Protecting farmers from open market instability brought on by global trends, gluts, and trader cartels is the foundation of their demands. With an average land holding of only 0.36 hectares, over 85% of farmers are small or marginal farmers who are extremely susceptible to price fluctuations.
- Guaranteeing farmers in underrepresented states equitable compensation and encouraging the production of non-cereal crops like oilseeds and pulses, legalizing MSP can help alleviate regional inequities. States like Bihar and Odisha are currently marginalized due to the current procurement bias towards Punjab and Haryana. For instance, the three states of Punjab, Madhya Pradesh, and Haryana accounted for 80% of the wheat purchased in 2021–2022. By guaranteeing equitable procurement across all regions, legalizing MSP would aid in the reduction of this disparity. Limited access to procurement: According to the 2015 report of the Shanta Kumar Committee, approximately 6–8% of farmers currently benefit from MSP (PIB, 2015).
- Increasing input costs, elevating the risk of agriculture, and reducing farmer self-harm and rural suffering. In 2022, 6,083 agricultural laborers died by suicide, according to NCRB data published in December 2023 (NCRB, 2023). By giving farmers a steady income, minimizing their reliance on credit, and preventing farmer self-harm, legal MSP helps ease rural suffering.
- A wish for respect and equality with other industries' minimum pay. The average monthly income of an Indian agricultural household is approximately ₹12698 (≈$150), according to the NABARD 2021 survey (PIB, 2024). The average monthly wage in India is ₹46,861 (US$561.33), while workers in non-agricultural industries such as construction make an average of ₹18,016 per month, and industrial laborers make even more. With the help of subsidies and organized markets, farmers in wealthy countries, on the other hand, make between $2,000 and $3,000 per month. Farm revenues are over two to three times greater, even in nations like Brazil and China. Due to this widening economic gap, where farming is the main source of income, there is a need for legal MSP.

In essence, farmers are not just asking for price support, but economic justice.

The Government's View: Welfare vs Viability

The Indian government and policy think tanks, such as NITI Aayog, have grave reservations about legalizing MSP, despite their sympathy for farmer aspirations:

- Fiscal Pressure: The financial impracticability of MSP is one of the main arguments against its legalization. According to estimates, the total market value of all crops covered by MSP might surpass ₹11 lakh crore every year. By contrast, the entire 2024–25 Union Budget came to about ₹48 lakh crore. Public finances would be severely strained if over one-fourth of the national budget were set aside just for MSP procurement. Furthermore, farmers usually save around 25% of their harvest for human consumption and animal feed, which makes extensive acquisition pointless and complicated. These issues demonstrate how economically unfeasible it is to enforce MSP as a legal right for all crops and geographical areas.
- Procurement Logistics: The restricted storage and distribution capabilities of organizations such as the Food Corporation of India (FCI) and state procurement bodies provide a significant obstacle to the legalization of MSP.
- Market Distortion: There is a chance that a legitimate MSP will cause agricultural markets to become distorted. It might impede crop diversification, result in overproduction of some products, and even drive out private traders who might not want to follow rigid pricing regulations. Furthermore, a significant portion of India's agricultural commerce takes place through unregulated or local channels, making legal MSP enforcement more difficult. The 2018 attempt by Maharashtra to impose MSP, which led to extensive trader boycotts and market disruptions, is a noteworthy example. This emphasizes how challenging it is to implement MSP consistently throughout India's varied and dispersed agri-markets (Anonymous, 2024).
- Inflationary Pressures: Mandating higher crop prices through legal MSP can trigger food inflation, disproportionately affecting low-income consumers. Economists estimate that a 1% hike in MSP may raise inflation by 15 basis points, threatening economic stability and increasing fiscal pressure through higher food subsidies and reduced affordability of essential commodities.
- WTO Implications: Legalizing MSP might be in violation of WTO regulations pertaining to agricultural subsidies, which could lead to disputes over international commerce. The necessity of carefully calibrating support measures to prevent international objections is shown by the fact that India has already used the WTO's Peace Clause to exceed rice subsidy restrictions.

Therefore, the government favours a market-driven, reform-based strategy over a legally enforceable procurement guarantee.

Is Legal MSP Legally Feasible?

According to the Concurrent List, a law may be passed under either Entry 14 (Agriculture) or Entry 33 (Trade and Commerce in Foodstuffs). However, in order to put it into practice, the Essential Commodities Act must be amended, and state-by-state price control mechanisms must be established. Enforcing procurement compliance in the private sector, which is difficult both legally and practically. Legal MSP may become symbolic legislation that ignores the true problems of price discovery and marketing access if it is not consistently implemented.

Alternatives to Legal MSP: Smarter, Sustainable Solutions

Experts recommend specific and adaptable approaches to legalizing MSP generally:

1. Price Deficiency Payment Scheme (PDPS): Using a direct transfer system, the government can reimburse farmers for the difference between MSP and market prices. The Bhavantar

Bhugtan Yojana has been tested in states like Madhya Pradesh, proving its viability (Sekhar, 2018).

2. Decentralized Procurement + Local PDS Integration: By involving state governments and local self-help groups in the procurement process, decentralization guarantees equitable benefit distribution and broader geographic coverage. For instance, local farmers have found success with Chhattisgarh's decentralized paddy procurement system. Purchase oilseeds, pulses, and millets locally from MSP and distribute them via anganwadis, PDS, or midday meals.
3. Direct Income Support (e.g., PM-KISAN + MSP Top-up): Simplify input subsidies to guarantee a minimum income through direct transfers instead of price support. After been successfully tested in Telangana's Rythu Bandhu scheme, this approach can be expanded across the country and connected to MSP guarantees to guarantee income support.
4. Reform of Crop Insurance and Input Subsidies: Price risk should be covered by redesigned crop insurance (PMFBY). Make use of smart subsidies that are connected to MSP adherence. Introduce climate-smart MSPs that account for hazards such as pest infestations and unpredictable rains. To provide climate-vulnerable farmers with a safety net, the system can connect MSP determination with insurance programs like PMFBY (Pradhan Mantri Fasal Bima Yojana).
5. Monitoring Digital MSPs and Integrating e-Markets: A real-time MSP monitoring dashboard should be created, Agricultural Produce Market Committees (APMCs) should be modernized and integrated with eNAM, and large-scale purchases below MSP should be penalized.

Conclusion: Beyond Legal MSP - Toward Assured Income

Deeper problems including pricing instability, institutional neglect, and market failure are reflected in the need for legal MSP. The discussion around the legalization of MSP brings to light the intricate relationship that exists between food security, fiscal sustainability, and farmer welfare. Legalizing MSP, however, might not be the answer. Indian farmers require composite solutions instead. Farmers want stable, equitable, and respectable livelihoods not simply increased prices. A dynamic combination of institutional, technological, and regulatory changes will be necessary to achieve that future rather than relying solely on legal coercion.

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SMART FISHERIES: THE ROLE OF IOT AND BLOCKCHAIN IN RESOURCE TRACEABILITY

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Abstract
India, the world's second-largest producer of farmed fish (aquaculture), had a fish farming market valued at USD 10.5 billion in 2024, projected to nearly double by 2033. The sector is advancing through technologies like Recirculating Aquaculture Systems (RAS), Bio- floc Technology (BFT), and automated monitoring systems, enhancing productivity and sustainability. Government programs like the "Pradhan Mantri Matsya Sampada Yojana (PMMSY)" promote climate resilience and infrastructure development. However, issues in sustainable resource use, conservation, and food safety persist. Digital tools such as IoT enable real-time monitoring, while blockchain ensures traceability, transparency, and compliance vital for tackling IUU fishing and meeting global market standards.

Keywords: IoT, blockchain, traceability, IUU fishing, aquaculture

Introduction
Smart fisheries involve "the integration of digital technologies, such as the Internet of Things (IoT) and blockchain, into the management and monitoring of fishery resources". These technologies facilitate real-time data collection, enhance supply chain transparency, and promote efficient resource utilization throughout the entire value chain from harvest to consumer (Joshi *et al*., 2024). In India, where fisheries contribute significantly to the economy and livelihoods, transitioning toward smart fisheries can modernize operations and enhance sustainability. India is one of the world's largest producers and exporters of fish and fishery products. Yet, the sector faces persistent challenges, including inadequate "traceability, illegal, unreported, and unregulated (IUU) fishing, post-harvest losses, and limited market transparency" (Widjaja *et al*., 2023). These issues hinder compliance with international trade standards and sustainable fisheries governance. With growing consumer demand for transparency, eco-labelling, and food safety, there is an urgent need to digitize fisheries operations to ensure product authenticity, improve management decisions, and secure market access (Salgado *et al*., 2025). IoT devices such as water quality sensors, GPS trackers, and RFID tags allow for continuous monitoring of fishing vessels, aquaculture systems, and environmental conditions. Meanwhile, blockchain technology ensures that the data collected is

secure, verifiable, and immutable, enabling end-to-end traceability across the supply chain (Prapti *et al*., 2022; Jais *et al*., 2024). When integrated, these technologies create a transparent and trustworthy digital ecosystem that benefits fishers, regulators, exporters, and consumers alike. For India, adopting such smart systems represents a strategic move toward building a resilient, inclusive, and future-ready fisheries sector.

Smart Fisheries in India

In the Indian context, "smart fisheries" refer to the integration of advanced digital technologies such as IoT, data analytics, remote sensing, and blockchain across the entire fisheries and aquaculture value chain. This approach aims to enhance production, management, traceability, and sustainability in both marine and inland fisheries. Smart fisheries leverage real-time data, automated monitoring, and digital platforms to optimize resource use, improve decision-making, and ensure environmental conservation (Rowan *et al*., 2023).

Government Initiatives Supporting Digitalization

PMMSY: The flagship scheme for fisheries development, PMMSY emphasizes modernization, infrastructure upgrades, and adoption of digital technologies to increase productivity, ensure traceability, and support sustainable practices.

Fisheries Information Management System (FIMS): FIMS is designed to collect, manage, and analyse fisheries data digitally, enabling better policy decisions, resource allocation, and monitoring of fishing activities.

Matsya Setu: This e-learning platform provides digital training and knowledge resources to fish farmers and stakeholders, promoting the adoption of smart technologies and best practices in aquaculture.

Potential of Smart Technologies in Marine and Inland Fisheries

Marine Fisheries: Smart technologies such as satellite-based navigation, IoT-enabled sensors, and real-time communication platforms improve safety at sea, optimize harvesting, and support compliance with regulations. Digital monitoring helps prevent "illegal, unreported, and unregulated (IUU) fishing, and supports sustainable resource management" through precise tracking of catches and vessel movements.

Inland Fisheries and Aquaculture: Precision aquaculture tools monitor water quality, feed usage, and fish health, enabling efficient farm management and reducing environmental impact. Data analytics and blockchain solutions enhance traceability from farm to market, ensuring food safety and building consumer trust. E-learning and digital advisory platforms empower farmers with knowledge and real-time support, accelerating the adoption of innovative practices.

Role of IoT (Internet of Things) in Fisheries and Aquaculture

The Internet of Things (IoT) is a system of interconnected physical devices embedded with sensors, software, and network connectivity, allowing them to collect, transmit, and share data (Sanusi *et al*., 2024; Yadav *et al*., 2025). In the fisheries sector, IoT enables real-time monitoring, predictive analytics, and informed decision-making, thereby increasing productivity, strengthening traceability, and supporting sustainable resource management (Fig. 1).

Core Technologies Used in IoT Applications

Sensors: Monitor "physical, chemical, and biological parameters like temperature, pH, dissolved oxygen, ammonia, turbidity, and salinity".

RFID (Radio Frequency Identification): Tracks fish batches, feed lots, and movement within the supply chain.

GPS (Global Positioning System): Enables vessel tracking, location-based monitoring of fishing zones, and fleet management.

Remote Monitoring Devices: Allow continuous surveillance and alert generation using cloud-based or mobile applications.

Applications of IoT in Aquaculture and Capture Fisheries

Water Quality Monitoring: Automated sensors monitor parameters like pH, DO, temperature, and ammonia levels to maintain optimal growing conditions.

Feeding Control Systems: Smart feeders use data analytics and sensors to deliver precise feed amounts, reducing waste and improving FCR (Feed Conversion Ratio).

Disease Monitoring and Early Warning: Bio-sensors and real-time health data collection help in early detection of disease outbreaks.

Stock Monitoring: Use of underwater cameras and sensors to estimate fish biomass and growth rates.

Vessel Tracking Systems (VTS): GPS and satellite-based trackers ensure real-time location tracking, enhancing safety and compliance with fishing zones.

Catch Documentation: Electronic logbooks and RFID systems record species, weight, and catch locations, ensuring traceability.

Gear Monitoring: IoT-enabled gear sensors monitor usage patterns and optimize gear deployment to reduce bycatch and habitat damage.

Illegal, Unreported, and Unregulated (IUU) Fishing Control: Surveillance through IoT-based systems enhances enforcement and regulatory oversight.

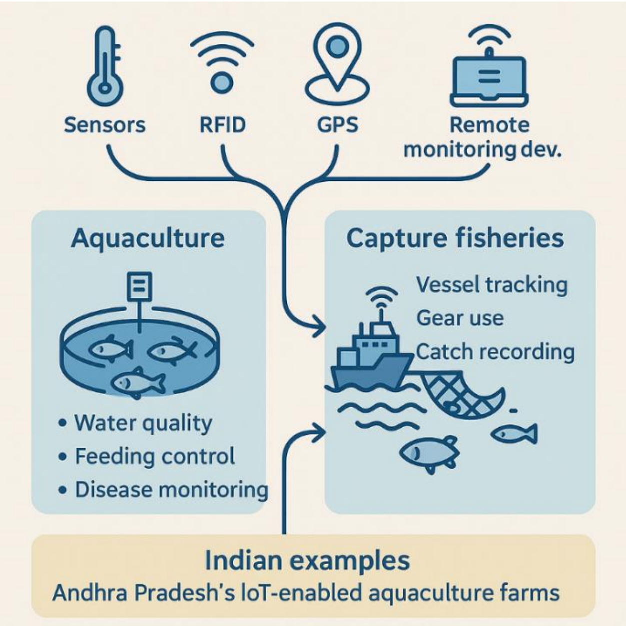

Fig.1 Role of IoT in aquaculture and capture fisheries

Role of Blockchain Technology in Fisheries and Aquaculture

Blockchain technology in fisheries ensures secure, transparent, and tamper-proof data recording, enhancing traceability from catch to consumer. It supports digital export certification, ensuring faster compliance with international standards. Food safety is improved through real-time tracking and rapid recall of unsafe products (Tolentino-Zondervan *et al.*, 2023). Eco-labelling and sustainability claims are verified via immutable records. It also combats IUU fishing and fraud by verifying species origin and handling (Fig. 2).

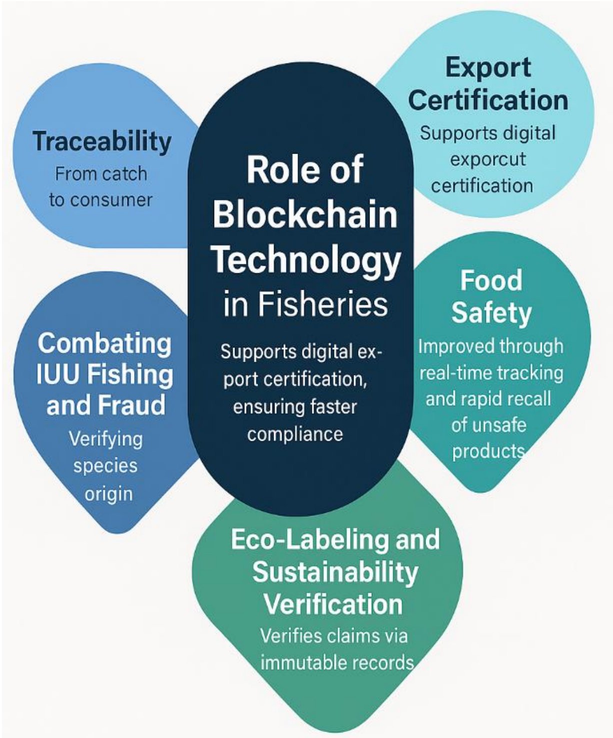

Fig 2. Roles of blockchain technology in Fisheries Resource Management

How IoT and Blockchain Integrate for Traceability

IoT devices (such as wireless sensors, RFID tags, and GPS chips) are deployed throughout the fisheries supply chain to continuously monitor and collect data on fish location, handling, environmental conditions (temperature, humidity), and biological parameters. This data is automatically and securely transmitted to a blockchain platform, where each transaction or event (e.g., catch, processing, packaging, shipping) is recorded as an immutable entry in a distributed digital ledger. Each fish or batch is assigned a unique identifier (via RFID, QR, or NFC codes), allowing stakeholders to trace its journey from capture or farm to the final point of sale or export. Integrating IoT (Yadav et al., 2025) and blockchain ensures real-time, tamper-proof traceability and accountability in fisheries. This boosts consumer trust, data accuracy, and operational efficiency across the supply chain (Fig. 3).

Fig. 3 Benefits of integrating IoT and blockchain in fisheries

Real-World Application: Tracking Fish from Capture to Market

When fish are caught or harvested, fishers record crucial details (species, location, time, weight, storage method) using IoT devices. As the fish moves through processing, packaging, and distribution, each handling event is logged on the blockchain, often triggered by IoT sensors or scanning devices. At any stage, stakeholders or consumers can scan a code on the packaging to instantly access the full digital history of the product, verifying its origin, handling, and compliance with standards.

Conclusion

The integration of smart technologies like the Internet of Things (IoT) and blockchain presents transformative potential for India's fisheries sector. These innovations enable real-time monitoring, operational efficiency, and traceability, addressing key challenges such as resource mismanagement, IUU fishing, and food safety. Enhanced transparency and accountability support regulatory compliance and improve market access. To harness these benefits, coordinated efforts from government, industry, and local communities are vital. Strategic investment, policy reforms, and digital literacy will drive adoption. Embracing smart technologies is essential to building a resilient, traceable, and sustainable fisheries sector aligned with India's Blue Economy and Digital India initiatives.

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NANOPARTICLES IN AQUATIC ENVIRONMENT, ITS IMPACTS

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Introduction

Nanoparticles (NPs) are materials with at least one dimension ranging from 1 to 100 nanometers (nm). Their extremely small size gives them distinct physical, chemical, and biological characteristics compared to their bulk forms. Features such as a high surface area-to-volume ratio, increased reactivity, and unique optical or electrical behaviours make NPs highly useful in fields like medicine, electronics, cosmetics, and environmental cleanup. Nevertheless, their presence in aquatic systems, whether from intentional applications, accidental releases, or natural formation has raised concerns about potential ecological and human health risks.

Entry and Fate of Nanoparticles in Aquatic Ecosystems

- **Pathways of Release:** Nanoparticles (NPs) enter aquatic systems through industrial effluents, municipal wastewater, surface runoff, emissions from nano-based products, and accidental releases.
- **Transformations in Water:** Once in the environment, NPs undergo physical (aggregation, agglomeration, sedimentation), chemical (dissolution, oxidation, sulfidation), and biological (biodegradation, bio-modification) alterations.
- **Influencing Factors:** Water properties such as pH, temperature, salinity, hardness, and the presence of natural organic matter play key roles in determining NP stability, dispersion, and toxicity.
- **Sediment Association:** A large fraction of NPs tends to settle into sediments, serving as a long-term sink and posing risks to benthic organisms while enabling trophic transfer.

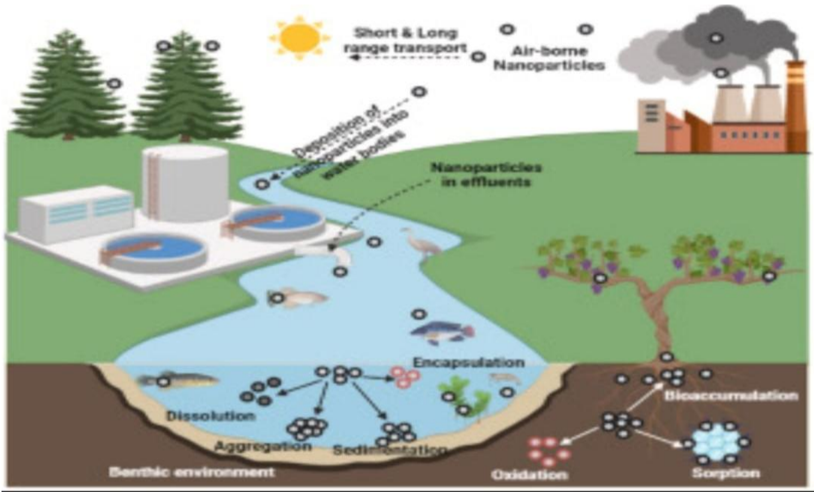

Fig.1 sources of nanoparticles into aquatic environment

Bioavailability and Uptake by Aquatic Organisms

- **Exposure Pathways:** Nanoparticles (NPs) can enter aquatic organisms through gills, skin, ingestion, or by direct cellular uptake, mainly via endocytosis.
- **Bioaccumulation:** NPs tend to accumulate in algae, invertebrates, and fish, leading to trophic transfer and potential biomagnification across the food web.
- **Size and Surface Effects:** The size, surface charge, and coating of NPs play a key role in determining their cellular uptake and associated toxicity.

Specific Nanoparticles and Their Impacts

- **Silver Nanoparticles (Ag-NPs):** Possess strong antimicrobial activity but can harm microbial communities and aquatic organisms by inducing reactive oxygen species (ROS).
- **Copper Nanoparticles (Cu-NPs):** Commonly used for their biocidal effects, yet they trigger oxidative stress and developmental toxicity in fish and invertebrates.
- **Titanium Dioxide Nanoparticles (TiO_2-NPs):** Associated with neurotoxicity, genotoxicity, and bioaccumulation, leading to behavioural changes and reduced survival.
- **Zinc Oxide Nanoparticles (ZnO-NPs):** Cause growth inhibition and organ damage in various aquatic species.

Toxicological Effects and Environmental Risks

- **Oxidative Stress:** A major pathway of NP toxicity is the overproduction of reactive oxygen species (ROS), which leads to oxidative stress, DNA damage, cellular dysfunction, and inflammation.
- **Physiological Impacts:** Exposure to NPs causes tissue-level alterations in vital organs such as the liver, gills, kidneys, and brain, while also disrupting reproduction, growth, and metabolic functions in aquatic organisms.
- **Species-Specific Sensitivity:** The degree of toxicity differs among species and life stages, with fish embryos and larvae being particularly vulnerable.
- **Ecological Implications:** NPs can disrupt community composition, nutrient dynamics, and primary productivity, ultimately threatening overall ecosystem balance.

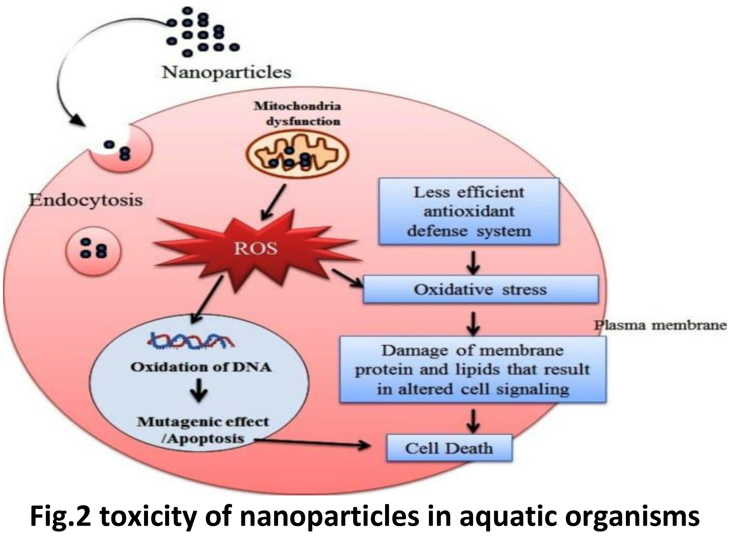

Fig.2 toxicity of nanoparticles in aquatic organisms

Types of Nanoparticles

Natural Nanoparticles

These originate from geological, chemical, or biological processes without human involvement.

- **Mineral-based NPs**: Include clay minerals (e.g., smectite, illite), silica, and iron oxides such as ferrihydrite, hematite, and goethite, as well as manganese oxides.
- **Carbon-based NPs**: Derived from natural organic matter, including humic and fulvic substances, along with carbon black formed during wildfires.
- **Biogenic NPs**: Produced by living organisms, such as magnetite from magnetotactic bacteria or calcium carbonate and silica shells formed by algae.
- **Colloidal NPs**: Nanosized aggregates of dissolved organic matter or inorganic colloids.

Engineered Nanoparticles (ENPs)

These are intentionally produced for industrial, medical, and commercial applications but can reach aquatic systems through wastewater, surface runoff, or accidental discharges.

- **Metal and Metal Oxide NPs**:
  - Silver (Ag-NPs): Used for antimicrobial purposes.
  - Titanium dioxide (TiO_2-NPs): Common in photocatalysts, sunscreens, and paints.
  - Zinc oxide (ZnO-NPs): Widely used in cosmetics and surface coatings.
  - Copper oxide (CuO-NPs): Applied in antifouling paints and as biocides.
  - Iron oxide (Fe_3O_4-NPs): Used in medical imaging and environmental remediation.
- **Carbon-based NPs**: Include fullerenes (C60), carbon nanotubes (CNTs), and graphene oxide.
- **Polymeric NPs**: Such as nanoplastics and polymer-based drug delivery systems.
- **Quantum dots and semiconductor NPs**: Examples include CdSe and CdTe, widely applied in electronics and imaging.

Incidental Nanoparticles

These are unintentionally produced as byproducts of human activities and subsequently enter aquatic environments.

- **Combustion-derived NPs**: Soot, black carbon, and fly ash generated from fossil fuel combustion, wildfires, or industrial emissions.
- **Wear-and-tear particles**: Released from the degradation of tires, brakes, paints, textiles, and coatings, breaking down into nanosized fragments.
- **Wastewater and sludge-related NPs**: Nanoplastics and metal oxides originating from sewage treatment processes.

Shapes of Nanoparticles

Nanoparticles in aquatic environments exhibit a variety of shapes, with spherical forms being the most prevalent. Advances in nanofabrication have broadened this range, leading to several distinct morphologies:

- **Spherical:** The most common form, occurring both naturally and in engineered nanoparticles.
- **Rod-shaped (nanorods):** Elongated particles with high aspect ratios, widely used in imaging and therapeutic delivery.
- **Cylindrical or filamentous:** Often seen in polymer-based nanoparticles, these shapes influence circulation time within biological systems.
- **Platelet-shaped:** Flat, plate-like structures that can alter flow dynamics and enhance heat transfer in nanofluids.

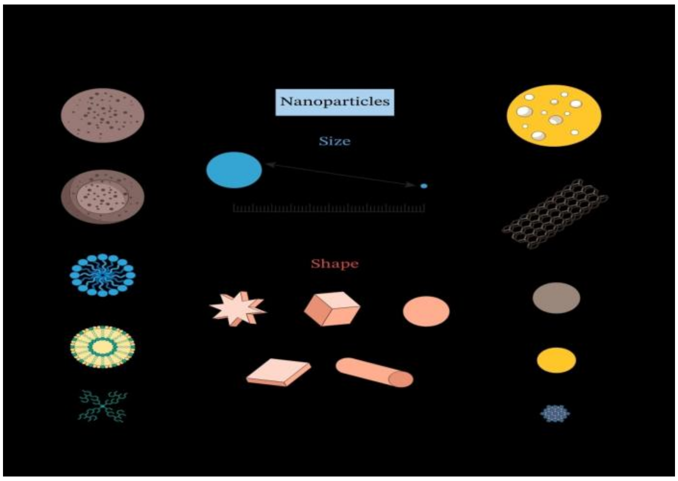

Fig.3 shapes and sizes of nanoparticles

Monitoring and Risk Management

- **Limited Standardized Data**: Information on environmental concentrations, long-term behaviour, and toxicity thresholds of nanoparticles remains insufficient.
- **Biomarker Use**: Indicators such as oxidative stress markers (e.g., antioxidant enzymes, heat shock proteins) and gene expression changes are employed to evaluate NP exposure and biological effects.
- **Regulatory Challenges**: The absence of clear guidelines for nanoparticle storage, transport, and disposal makes effective risk management difficult.
- **Need for Further Research**: There is an urgent demand for ecological risk assessments across different trophic levels, with greater focus on trophic transfer, chronic exposure, and impacts at the ecosystem scale.

Remediation strategies of Nanoparticles

Physical Methods

- **Filtration & Membrane Systems:** Techniques such as nanofiltration, ultrafiltration, and reverse osmosis are effective in removing nanoparticles from wastewater before they enter natural water bodies.
- **Sedimentation and Coagulation–Flocculation:** The addition of chemical coagulants like alum, ferric salts, or natural biopolymers (e.g., chitosan) promotes the aggregation of nanoparticles into larger particles, making them easier to settle and remove.
- **Adsorption:** Materials such as activated carbon, biochar, zeolites, and clay minerals can adsorb nanoparticles, reducing their concentration and mobility in aquatic systems.

Chemical Methods

- **Advanced Oxidation Processes (AOPs):** Methods like photocatalysis, ozonation, and Fenton reactions break down organic coatings on engineered nanoparticles, decreasing their toxicity.
- **Redox Manipulation:** The addition of reducing or oxidizing agents (such as sulfides or ferrous iron) alters nanoparticle stability, encouraging precipitation or transformation

Biological Methods

- **Microbial Bioremediation:** Specific bacteria, fungi, and algae can capture, transform, or immobilize nanoparticles through processes like biosorption and bioaccumulation.

- **Phytoremediation:** Aquatic plants such as duckweed and water hyacinth can absorb or trap nanoparticles, contributing to water purification.
- **Biofilm-Assisted Removal:** Microbial biofilms secrete extracellular polymeric substances (EPS), which promote nanoparticle aggregation and sedimentation.

Preventive & Management Measures

- **Source Reduction:** Minimizing nanoparticle release through eco-friendly nanotechnology and the design of safer nano-enabled products.
- **Regulation and Monitoring:** Establishing discharge standards, monitoring nanoparticle levels, and developing standardized detection techniques.
- **Upgrading Treatment Facilities:** Incorporating advanced processes such as membrane bioreactors or specialized adsorbents into existing wastewater treatment plants for more effective nanoparticle removal into less harmful forms.
- **pH and Ionic Strength Control:** Adjusting water chemistry can enhance aggregation and sedimentation of nanoparticles, aiding in their removal.

Conclusion

Nanoparticles, with their unique nanoscale characteristics and expanding applications, have emerged as a new class of contaminants in aquatic systems. Their transformations, bioavailability, and toxic effects present significant risks to organisms from microbes to fish, disrupting physiological processes and threatening overall ecosystem health. Understanding their environmental behaviour and impacts calls for interdisciplinary research and stronger regulatory measures to protect aquatic life and maintain water quality.

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INNOVATIONS IN AQUARIUM FABRICATION: MATERIAL, TECHNOLOGY, AND SUSTAINABLE DESIGN

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Abstract

Innovations in aquarium fabrication are dramatically reshaping the industry, driven by advancements in materials science, digital manufacturing, and sustainability objectives. This article explores the latest breakthroughs in tank construction materials, modern manufacturing technologies, and the integration of eco-friendly practices that enable aquariums to be stronger, clearer, lighter, and more sustainable than ever.

Introduction

From simple glass rectangles housing fish to immersive, architecturally striking aquatic ecosystems, aquariums have evolved into sophisticated interfaces between humans and aquatic biodiversity. The increasing demand for large-scale public exhibits, conservation facilities, and eco-friendly home aquaria has propelled innovation in fabrication materials and technology. Priorities today include maximizing durability, minimizing environmental impact, enhancing animal welfare, and delivering captivating visual experiences through smart automation and sustainable design.

Innovations in Materials:

Glass: Traditional Strength, Modern Refinements

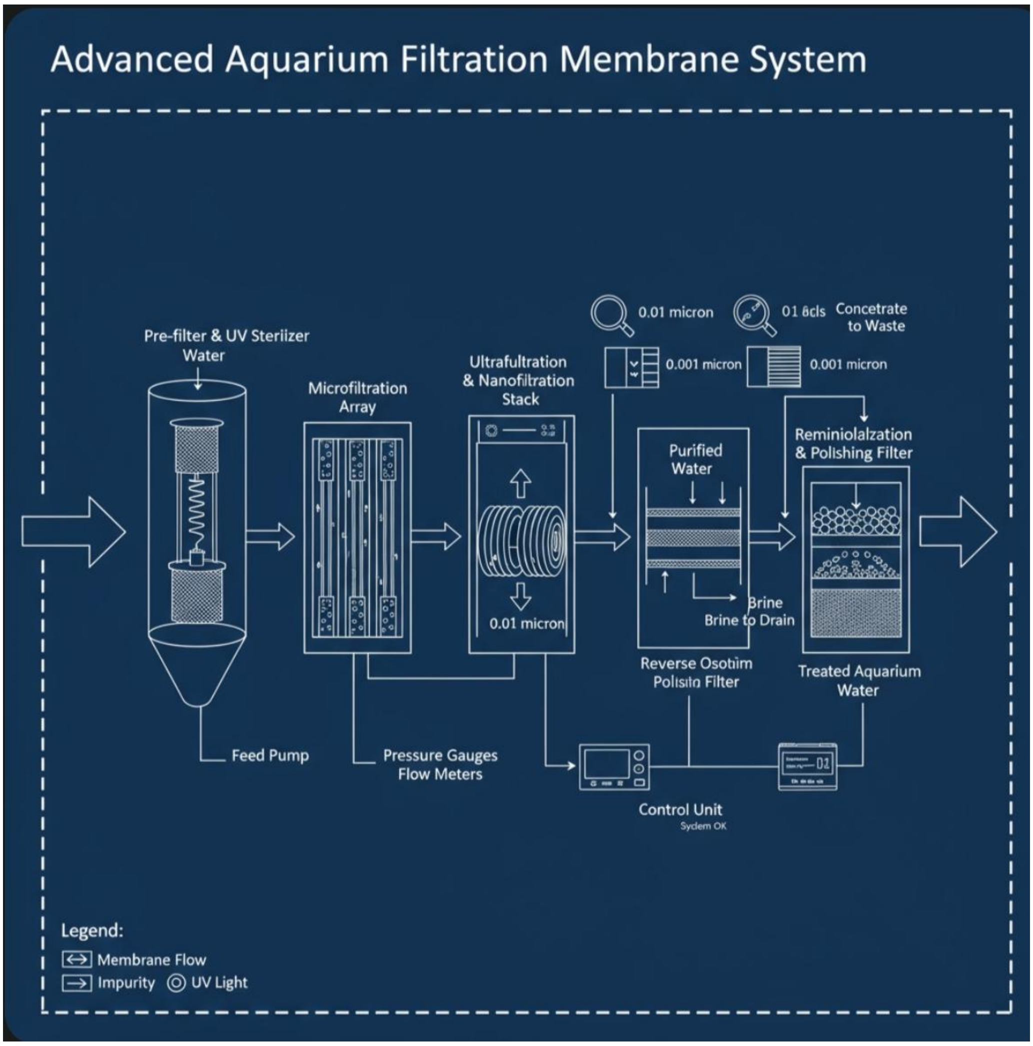
- Tempered Glass remains a foundational material, prized for strength and safety. Recent production improvements emphasize energy-efficient manufacturing and low-iron variants to improve optical clarity.
- Low-Iron Glass (ultra-clear) enhances viewing experiences in public aquariums and museum exhibits.
- Transparent Composites emerging from materials research blend the best attributes of glass and polymers, offering toughness with excellent clarity and light weight.

Acrylics and Eco-Conscious Polymers

- High-Grade PMMA Acrylic dominates for large-scale tanks due to its superior clarity, impact resistance, and adaptability into complex shapes like curved panels, tunnels, and domes. Thicknesses range up to 120mm based on application.
- Sustainable Acrylic Blends incorporating recycled content and bio-based monomers reduce carbon footprint while maintaining performance.
- Engineering plastics such as ABS, HDPE, and PEX form critical structural frames, plumbing, and filtration housing, balancing chemical resistance and durability.

- Bio-Inspired Biocomposites, notably mycelium-derived materials, are emerging as biodegradable decor and backdrop substitutes, pushing toward fully sustainable tank accessory ecosystems.

Advanced Filtration Membranes



Inspired by industrial liquid separation, polymeric membranes now improve aquarium filtration with enhanced permeabilities, antifouling surface chemistry, and extended lifecycle, playing a vital role in efficient recirculating aquaculture systems.

Technological Breakthroughs in Fabrication and Control:

Digital and Additive Manufacturing ;

- CNC Machining and Laser Cutting enable precision shaping of tank components, ensuring leak-tight joins and reducing waste through computer-aided design and manufacturing (CAD/CAM).
- 3D Printing facilitates rapid prototyping and creation of bespoke fittings, filtration parts, and ornamental elements, shortening design cycles and enhancing customization.
- Laser Welding and Solvent Fusing techniques produce seamless acrylic joints that improve structural integrity and aesthetic finish.

Intelligent Aquarium Systems and IoT Integration

- Sensor Networks continuously measure parameters such as pH, temperature, salinity, dissolved oxygen, and water quality.
- Artificial Intelligence applies predictive analytics for early disease detection, optimized dosing, and adaptive life support, reducing manual labor and improving animal health outcomes.
- Remote Monitoring and Cloud Platforms grant owners and facility operators real-time insights and alerts for proactive maintenance.
- Robotic Feeders and Automated Aquascaping technologies manage nutrition and tank aesthetics with high species-specific precision.

Energy-Saving Lighting and Support Systems

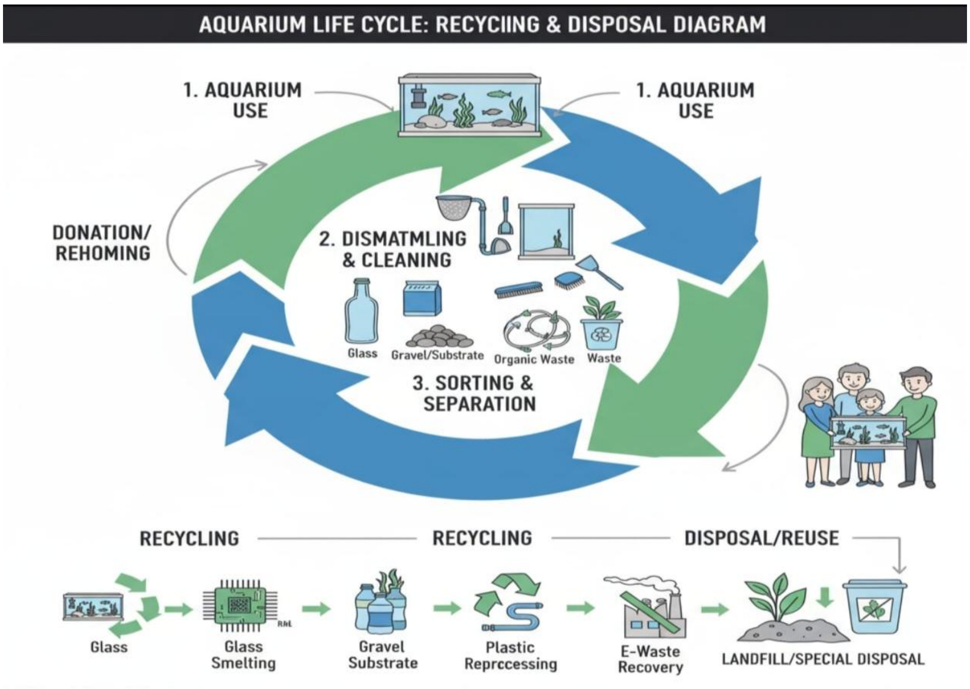
- Spectrum-Tunable LEDs mimic natural daylight and lunar cycles, improving coral and plant growth while reducing energy consumption (<20 W/m^2 typical).
- Environmental Simulation of diurnal, lunar, and weather patterns reduces stress in sensitive species and enhances exhibit realism.
- Recirculating Aquaculture Systems (RAS) with multi-stage biological and polymeric membrane filtration coupled with UV and ozone sterilization dramatically reduce water use and chemical dependence.

Sustainable Design and Circular Economy

Water and Resource Management

- RAS Adoption across the hobbyist and commercial sectors offers 100-fold water conservation over conventional methods, enabling closed-loop, low-waste operation.
- Integrated Aquaponics merges fish cultivation with plant growth, utilizing fish waste as fertilizer and plants as biofilters, creating symbiotic, sustainable aquatic-terrestrial ecosystems.
- Water and Energy Optimization increasingly leverages solar, daylighting strategies, and energy recovery to lower operational footprints.

Lifecycle and End-of-Life Strategies



- Modular Construction enables repair, upgrades, and part replacement, prolonging useful lifespan.
- Manufacturer Take-Back Programs promote responsible material reuse and recycling.
- Use of Biodegradable and Recycled Materials for pumps, fittings, decorations, and filtration media reduces plastic pollution.

Sustainable Sourcing and Material Innovation

- Emphasis on locally sourced recycled glass, bio-based acrylic monomers, and renewable composites (e.g., bamboo fibers, mycelium) reduces embodied carbon.
- Life Cycle Assessments (LCA) are used to optimize environmental impact across manufacturing chains.

Emerging Trends and Future Directions

Immersive Public Engagement and Education

- Augmented and Virtual Reality (AR/VR) augment visitor experiences, offering interactive, multi-sensory education on aquatic ecosystems and conservation.
- Holographic Displays and Touchscreens enhance engagement in museum and exhibit contexts.

AI-driven Animal Welfare and Predictive Care

- Advanced computer vision and machine learning monitor animal behavior and health indicators non-invasively, enabling predictive interventions.
- Autonomous systems ensure optimal environmental balance and nutrition with minimal human input.

Biomimicry and Smart Materials

- Experimental materials mimicking natural marine structures (e.g., dynamic light-filtering membranes) offer adaptive responses to environmental stressors.

- Hybrid materials integrating sensor arrays and filtration channels can become a standard as additive manufacturing capabilities mature.

Modern Aquarium Specifications (2025 Example)

Feature	Specification / Benefit
Acrylic Panels	Recycled-content or bio-based PMMA, 30–120 mm thickness
Glass Alternatives	Low-iron tempered panels, 10–30 mm, ultra-clear
Frame Materials	Recycled aluminum, biodegradable plastics, bamboo composites
Plumbing	UV-cured PVC, HDPE, PEX, and biodegradable bio-plastics
Joints	Solvent-welded acrylic, laser-fused, or silicone sealed
Filtration Systems	Multi-stage: mechanical, biological filters, polymer membranes
Lighting Systems	IoT/AI-controlled, spectrum-tunable LEDs
Automation	IoT+AI integration with remote monitoring and predictive alerts
Sustainable Features	RAS, ozone/UV sterilization, aquaponics integration, green energy
End-of-Life Management	Modular, repairable, manufacturer recycling/take-back programs

Conclusion

Aquarium fabrication today stands at the confluence of advanced materials engineering, digital manufacturing, smart automation, and ecological stewardship. This integration facilitates the creation of aquariums that are not only visually stunning and robust but also environmentally responsible and highly attuned to the needs of aquatic life. With the rise of closed-loop systems, AI-driven monitoring, and sustainable material cycles, the future of aquarium displays holds promise for both public enjoyment and conservation impact. By embracing these innovations, aquarium manufacturers, hobbyists, and researchers collaboratively push toward a vibrant, sustainable underwater future.

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AQUATIC POLLUTION & CONSERVATION CHALLENGES

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Abstract

Aquatic environments are facing an unprecedented burden from pollution, threatening biodiversity, food security, and human health. This article explores current research and pressing issues in aquatic pollution—specifically microplastics and pharmaceutical contaminants—and highlights innovative coral reef restoration methods as a beacon of conservation hope. The report covers sources, transport, and impacts of emerging pollutants, their eco-toxicological effects, and global best practices in restoration.

Introduction

Aquatic ecosystems rivers, lakes, and oceans are vital to planetary health and human well-being. Yet, they are under siege from an array of pollutants, notably microplastics and pharmaceutical residues (Varsha *et al*., 2025). These contaminants not only disrupt aquatic food webs but also pose risks to humans through bioaccumulation. Conservation efforts, including advanced coral reef restoration, offer actionable hope to reverse or mitigate some of these impacts (Pirali zefrehei *et al*., 2022).

1. The Microplastic Maze: From Freshwater Rivers to Deep Ocean Trenches

- **Sources of Microplastics:**
  - Industrial runoff (manufacturing beads, pellets).
  - Urban waste (plastic packaging, synthetic textiles).
  - Agricultural runoff, atmospheric deposition.
  - Degradation of larger plastics (secondary microplastics)(Varsha et al., 2025).
- **Transport Mechanisms:**
  - River flow, wind, tidal currents, and storm runoff drive global dispersion from freshwater to marine and deep-sea environments.
  - Microplastics accumulate in sediments, water columns, and surface microlayers, leading to contamination hotspots.
- **Ecological and Human Impacts:**
  - Ingestion by fish, plankton, and invertebrates causes intestinal blockages, reduced feeding, stunted growth, and reproductive toxicity.
  - Microplastics can act as vectors for heavy metals and organic pollutants, increasing risks of inflammation and oxidative stress up the food chain, including humans.
- **Emerging Solutions:**
  - Wastewater treatment upgrades targeting smaller particles.
  - Policy interventions banning microbeads and limiting single-use plastics.
  - Research into biodegradable plastics as an alternative.

Source	Transport	Ecological Impact	Human Health Concern
Industrial runoff	Rivers	Ingestion by aquatic organisms	Chemical bioaccumulation
Urban/Atmospheric	Wind/Ocean	Habitat contamination	Food-chain transfer
Degraded plastics	Currents	Microbial community disruption	Inflammation, toxicity

2. Pharmaceuticals in Our Waterways: The Silent Threat

- **Sources & Prevalence:**
  - Input from municipal wastewater, pharmaceutical manufacturing, and agricultural runoff.
  - Most wastewater treatment plants cannot fully remove pharmaceutical compounds, leading to global waterway contamination (Fois *et al*., 2021).
- **Ecological Effects:**
  - Behavioral alterations in fish, including reduced predator avoidance and mating disruption.
  - Gender alteration and reproductive decline due to hormone-mimicking compounds.
  - Changes in microbial communities, risking ecosystem-level nutrient cycling (Barros & Seena, 2022).
- **Human Health Risks:**
  - Potential for antibiotic resistance spread.
  - Long-term, low-level exposure concerns remain under investigation.

- **Strategies for Removal:**
    - Advanced filtration ozonation, activated carbon, membrane bioreactors.
    - Nature-based solutions constructed wetlands, phytoremediation.
    - Policy: Source reduction, drug take-back programs, green chemistry incentives.

3. Coral Reef Restoration: Hope on the Horizon

- **Why Reefs Matter:**
    - Coral reefs anchor ~$375 billion in annual ecosystem services: coastal protection, fisheries, tourism, and biodiversity (Campbell *et al*., 2022).
    - Up to 90% of reefs may be lost by 2050 without urgent action.
- **Restoration Techniques:**
    - **Coral Gardening:** Fragments grown in nurseries then transplanted onto degraded reefs.
    - **Larval Propagation:** Cultivation and seeding of coral larvae to boost genetic diversity and resilience.
    - **Substrate Manipulation:** Stabilizing rubble or adding artificial structures to foster regrowth.
    - **Gene Editing:** Research into selectively breeding or editing corals for heat resistance.

Restoration Benefits:

- Restored reefs can help buffer coastlines, renew fisheries, and offer tourism value.
- Promotes stewardship among local communities and supports national climate, biodiversity, and sustainability goals.

Conservation in the Face of Aquatic Pollution

Conserving aquatic environments amidst escalating pollution challenges demands coordinated and innovative efforts. Sustainable management of water resources should focus on both preventing ongoing contamination and restoring already degraded ecosystems. Successful conservation approaches include:

- **Implementing Strict Pollution Controls:** Enforce regulations to minimize industrial, agricultural, and domestic runoff, targeting contaminants such as heavy metals, pesticides, excess nutrients, plastics, and emerging pollutants like pharmaceuticals and microplastics.
- **Promoting Ecosystem Restoration:** Restore and rehabilitate degraded rivers, lakes, wetlands, and coastal zones, using techniques such as re-establishing native vegetation, improving natural water flows, and removing obsolete dams where feasible.
- **Advancing Wastewater Treatment:** Invest in modern wastewater treatment technologies capable of removing a wider range of pollutants, including pharmaceutical residues and microplastics, before discharge into natural water bodies.
- **Fostering Community Engagement and Education:** Encourage public participation and raise awareness about the importance of conserving aquatic ecosystems, the impacts of pollution, and practices that reduce individual and collective environmental footprints.
- **Strengthening Monitoring and Research:** Support multidisciplinary research and robust monitoring systems to identify pollution hotspots, assess cumulative ecological impacts, and inform adaptive management strategies.
- **Integrating Policy and Local Action:** Develop comprehensive policies that combine governmental regulation, scientific input, and local stakeholder involvement, ensuring that conservation goals are supported by both top-down and grassroots initiatives.

These strategies are crucial not only to safeguard biodiversity and ecosystem services but also to protect human health and livelihoods that are closely intertwined with the integrity of aquatic environments.

Conclusion

The global aquatic environment faces mounting pollution challenges from microplastics and pharmaceuticals, with far-reaching effects on wildlife and potentially human health. Addressing these issues requires integrating technological innovation, stricter pollution controls, and embracing ecosystem-focused conservation solutions. At the same time, targeted approaches such as coral reef restoration provide grounds for optimism demonstrating how science, community action, and policy can come together for the sustainable future of aquatic life.

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IMPORTANT DISEASES OF MAIZE AND APPROACHES TO THEIR MANAGEMENT IN INDIA

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Introduction

Maize (*Zea mays* L.), often called the "Queen of cereals," is one of the most important cereal crops grown worldwide. It is highly versatile and adaptive to different climates, and it is used as food, feed, and for industrial purposes such as starch, oil, beverages, and sweeteners. However, maize productivity is severely affected by diseases caused by fungi, bacteria, viruses and nematodes. Globally, about 115 diseases of maize are reported; in India around 60, but only 10-12 cause serious yield losses. Average losses are about 13%, but under severe epidemics it can be much higher. Understanding the symptoms, causal organisms, favorable conditions, and management practices of maize diseases is essential for effective crop protection and food security.

Major Diseases of Maize

The economically most important maize diseases are namely blights, rots, leaf spot, rusts and downy mildew. The details symptoms, etiology, epidemiology, disease cycle and management of most common diseases of maize in India as follows.

(1) Maydis Leaf Blight (MLB) / Southern Corn Leaf Blight (SCLB)

Economic Importance:

Prevalent in nearly all maize-growing regions of India. Yield losses may reach 70% or more under favorable conditions. Severity depends on fungal race (O or T), crop stage, and environmental conditions.

Symptoms:

On leaves Small, diamond-shaped lesions with straw-colored centers and dark margins. Lesions elongate but are restricted by veins. In severe cases, lesions coalesce, blighting entire leaves and giving a scorched field appearance.

Sheaths, stalks, husks, ears and cobs may show necrotic patches, darkened tissue, and premature drying. In advanced stages, lesions darken due to spore production, appearing gray, olive, or black. Visual symptoms supported by lab confirmation for accurate identification.

Etiology

Teleomorph*: Cochliobolus heterostrophus* (Drechsler) Drechsler, 1934
Anamorph synonyms:

1. *Bipolaris maydis* (Y. Nisik. & C. Miyake) Shoemaker, 1959

2. *Drechslera maydis* (Y. Nisik. & C. Miyake) Subram. & B.L. Jain, 1966
3. *Helminthosporium maydis* Y. Nisik. & C. Miyake, 1926

There are three physiological races of *B. maydis*: Race T, Race O and Race C. The conidia are olivaceous brown, spindle-shaped, tapering to rounded ends, measuring 15-20×0-160 µm, and typically possess 5 to 11 septa with characteristic bipolar germination. The asci are cylindrical and hyaline, while the ascospores are dark, measuring 6-7×130-340 µm, and generally contain 5 to 9 septa.

Favorable conditions
Warm humid weather (20–30°C, >80% RH). **Disease Progression** suppressed by prolonged dry, sunny weather. Pathogen survive in infected plant debris on soil surface or inside seed but buried debris at 5-20 cm depth pathogen fails to survive. Temperature range of 20-28°C and 20°C-24°C is necessary for sporulation of conidia for race O and T respectively. Wind-borne conidia initiate secondary infection, wind speed ≥18 km/h required for conidial detachment and dispersal.

Disease cycle
The fungus survives between cropping seasons as mycelium in infected crop residues that persist on the soil surface. With the onset of a new growing season, under favorable temperature and humidity, the mycelium present in the debris initiates sporulation, producing conidia. These conidia are dispersed by wind currents and rain splash to nearby maize plants. Upon reaching susceptible hosts, the conidia germinate and penetrate primarily through stomata, resulting in the development of characteristic foliar lesions. Within these lesions, secondary conidia are produced, facilitating repeated cycles of infection. Under conducive environmental conditions, the entire disease cycle may be completed within 72 hours, enabling rapid epidemic development.

Integrated Disease Management (IDM)
1. Cultural Practices
   a) Remove and destroy infected crop residues post-harvest
   b) Deep plowing to bury debris beyond survival depth
   c) Crop rotation with non-hosts (e.g., legumes)
   d) Avoiding excess nitrogen can also help prevent the conditions that favor the disease.
2. Resistant Hybrids
   a) Use resistant or tolerant varieties (like Deccan, VL 42, Prabhat, KH-5901, PRO-324, PRO-339, ICI-701, F-7013, F-7012, PEMH 1, PEMH 2, PEMH 3, Paras, Sartaj, Deccan 109).
   b) Consult local extension services for updated hybrid lists
3. Seed Treatment:
   a) Thiram 75 WS @ 3 g/kg seed
   b) Reduces early-stage infection and inoculum load
4. Fungicidal Sprays:
   a) Foliar spray with Indofil M-45 (Mancozeb) fungicide 2.5 grams per liter of water.
   b) Azoxystrobin 18.2% + Difenconazole 11.4% w/w SC at the rate of one milliliter of the fungicide per liter of water apply as a foliar spray.
   c) Spray propiconazole 25% EC @ 1ml/l on 35 and 50 days after sowing.
   d) Seed treatment with Thiram @ 3 g / kg seed+ Foliar spray with Mancozeb 75 WP (2.5 g/litre water) at 45 DAS+ Foliar sprays with Azoxystrobin 18.2% w/w+ Difenoconazole 11.4% w/w SC @1 ml/l water at 55 days after sowing.

(2) Turcicum Leaf Blight (TLB) / Northern Corn Leaf Blight (NCLB)

Economic Importance

The disease was first reported in India by Butler in 1907 from Bihar and is now prevalent across nearly all maize-growing regions of the country, particularly prevalent in the hilly and humid regions of **Jammu & Kashmir, Uttarakhand, Himachal Pradesh, the North-Eastern states, West Bengal, Karnataka, and Bihar**. It has been associated with severe epiphytotic outbreaks, resulting in substantial grain yield losses ranging from 25% to as high as 90%, depending on disease severity and environmental conditions. The pathogen causes premature death of blighted leaves, thereby reducing the effective photosynthetic area and leading to significant yield reductions. In particular, large-scale epidemics have been documented in Karnataka, where yield losses of 28–91% have been reported, highlighting its status as one of the most devastating foliar diseases of maize in India.

Etiology

Teleomorph: *Setosphaeria turcica* (Luttr.) K.J. Leonard & Suggs, 1974
Anamorph synonyms:

a. *Exserohilum turcicum* (Pass.) Leonard and Suggs, 1974
b. *Bipolaris turcica* (Pass.) Shoemaker, 1959
c. Drechslera turcica (Pass.) Subram. & B.L. Jain, 1966
d. Luttrellia turcica (Pass.) Khokhr., 1978
e. Helminthosporium turcicum Pass., 1876
f. Helminthosporium inconspicuum Cooke & Ellis, 1878

Ascomata: Black, globose to elliptical, ostiolate, measuring 350–725 × 345–500 µm.
Setae: Rigid, dark brown, thick-walled, septate, up to 150 µm long and 4–6 µm thick.
Pseudoparaphyses: Filiform, hyaline, septate, branched, and anastomosing.

Asci: Cylindric-clavate, short-pedicellate, bitunicate, thick-walled when young, 1–8 spored, measuring 175-250×24-31 µm.

Ascospores: Hyaline, fusoid, mostly 3-septate (range 1-6), constricted at septa, straight to slightly curved, 40-78 ×12-18 µm, surrounded by a thin hyaline mucilaginous sheath that may extend beyond the spore ends after discharge.

Conidiophores: Arising singly or in small groups, simple, cylindrical, olivaceous-brown (paler at apex), geniculate above, up to 300 µm long and 8-10 µm thick; emerge through stomata or occasionally through the epidermis.

Conidia: Ellipsoidal to obclavate, pale to olivaceous-brown, straight to slightly curved, smooth, 4-9 distoseptate, measuring 50-144×18-33 µm, with a distinct protuberant hilum. Germination occurs predominantly from one or both polar cells, rarely from intermediate cells.

Symptoms

The disease usually begins on the lower leaves as **small, elliptical, water-soaked or light tan spots**. In susceptible cultivars, these lesions expand to form **elongated, cigar-shaped necrotic lesions** measuring **1–6 inches in length**. As infection progresses, lesions may coalesce, resulting in **extensive leaf blight and scorching**, giving the field a burnt appearance. Severely affected plants exhibit **widespread browning and necrosis**, leading to significant reduction in photosynthetic area and grain yield.

Epidemiology / Favourable Conditions

The disease develops most rapidly under **cool, wet, and humid conditions**. An optimum temperature range of **18–27°C** combined with **relative humidity of around 75%** is highly favourable. Extended periods of leaf wetness due to dew, rainfall, or irrigation further enhance disease development and spread.

Disease cycle

The fungus survives in infected crop residues present in or on the soil, where mycelia and conidia serve as the primary inoculum for subsequent crops. Conidia are capable of persisting between seasons by developing thickened walls and transforming into chlamydospores. During the growing season, secondary inoculum arises from conidia produced on foliar lesions, which are efficiently dispersed by wind and may be transported over long distances, facilitating rapid disease spread.

Management

Effective management of Turcicum leaf blight requires an **integrated approach**:

- **Cultural practices**:
  - Follow crop rotation with non-cereal crops and destroy crop debris after harvest to reduce inoculum carryover.
  - Crop rotation with non-hosts (e.g., legumes)
- **Resistant/tolerant hybrids**:
  Use region-specific resistant maize hybrids to minimize losses (like DMRH 1308 and DMRH 1301).
- **Chemical control**:
  In high disease pressure areas or when susceptible cultivars are grown, apply fungicides. Recommended options include:
  - **Spraying of Azoxystrobin 18.2% + Difenconazole 11.4% SC @ 1 ml/L of water.**
  - **Foliar spray of Mancozeb (Indofil M-45) @ 2.5 g/l of water.**
    The first spray should be given **at the initial appearance of symptoms**, followed by a **second spray after 10-15 days** if conditions remain favourable for disease.

(3) Banded Leaf and Sheath Blight (BLSB)

Economic importance

Banded leaf and sheath blight (BLSB) is recognized as one of the most destructive sheath and ear diseases of maize in India, posing a major constraint to maize production. Yield losses commonly range from 11–40%, depending on environmental conditions and varietal susceptibility, but under epiphytotic situations, reductions of up to 90% have been reported (Lal *et al*., 1985). Earlier studies by Singh and Sharma (1976) highlighted losses in grain yield between 11-40%. The disease is prevalent across all major maize-growing states, including Himachal Pradesh, Uttar Pradesh, Haryana, Punjab, Madhya Pradesh, Chhattisgarh, Rajasthan, Andhra Pradesh, West Bengal, Telangana, Delhi, Uttarakhand (Pantnagar), and the North-Eastern states. It is particularly severe in the hot, humid foothill regions of the Himalayas as well as in the plains, where environmental conditions strongly favour its development.

Characteristics symptoms for identification:

- Symptoms typically appear at 40–50 days after sowing, although exact timing may vary with environment.

- The characteristic lesions are first seen on lower leaves and sheaths (first and second) in the form of concentric bands and rings. The first signs are water-soaked lesions with a straw-coloured appearance on the basal leaf sheaths.
- These lesions develop into alternating dark brown bands.
- As the disease advances, lesions enlarge and coalesce, spreading upwards from the base to higher leaves.
- In later stages, dark brown sclerotia (hardened fungal masses) appear on leaf sheaths, husks, and cobs, ensuring pathogen survival and spread.
- Severe infection leads to premature drying and rotting of developing cobs, resulting in poor grain filling, reduced yield, and inferior quality.

Etiology

Asexual stage: *Rhizoctonia solani* f. sp. *sasakii* Kuhn
Sexual stage (teleomorph): [*Thanatephorus cucumeris* (Frank) Donk]

Mycelium

The hyphae exhibit Septate, hyaline when young, becoming brown with age and typically branch at right angles, with a subtle (slight) constriction at the base of lateral branches. Hyphal diameters range from 5 to 14 µm. The mycelium is characterized by dolipore septa and multinucleate cells. Notably, the fungus does not produce asexual spores. In culture, it frequently forms sclerotia and may develop barrel-shaped cells within infected plant tissues.

Sclerotia

Sclerotia are of the loose type, initially pale but progressively darken to a reddish-brown hue. The central region comprises pseudoparenchymatous tissue, contributing to structural integrity and resilience under adverse conditions.

Epidemiology / Favourable conditions:

The disease is favoured by high relative humidity (90%), optimum temperature of around 28°C, and rainfall during the early stages of crop growth (especially within the first week of infection). Such conditions accelerate the development and spread of the pathogen.

Disease Cycle

The pathogen exhibits remarkable longevity, capable of surviving in soil for extended periods. This persistence is primarily attributed to the thick, melanized outer layer of its sclerotia, which confers protection against environmental extremes and facilitates overwintering.

In rare instances, particularly in its teleomorphic stage, the pathogen may persist as vegetative mycelium. Host attraction is mediated by chemotactic responses to specific exudates released by actively growing plant tissues. The infection process is initiated through multiple entry mechanisms:

Direct penetration of the plant cuticle or epidermis. Exploitation of natural openings, such as stomata or wounds. Formation of appressoria, specialized structures that exert mechanical pressure to breach host cells. Secretion of cell wall-degrading enzymes, facilitating tissue maceration and entry. Following successful invasion, the pathogen colonizes necrotic tissues, proliferates within the host, and subsequently forms sclerotia. These structures serve as reservoirs for new inoculum, which may be produced either on the surface or internally within host tissues.

Survival Phase: Sclerotia or residual mycelium overwinter in soil, plant debris, or infected host tissues.

Initiation Phase: Under favourable conditions, germination occurs. Hyphae emerge and, in rare cases, fruiting bodies (basidia) may develop, occasionally producing basidiospores.

Infection and Reproduction: The pathogen infects new hosts, colonizes tissues, and completes its reproductive cycle by forming new sclerotia, thereby perpetuating the disease cycle.

Management

An integrated approach is required to minimize disease incidence and losses:

1. Cultural practices
    - Strip the lower 2-3 leaves with their sheaths that come into contact with the soil, reducing inoculum spread.
    - Practice crop rotation with non-host crops and maintain proper field sanitation.
2. Fungicidal application
    - Apply Azoxystrobin 18.2% + Difenoconazole 11.4% SC @ 1 ml/L water at the first appearance of symptoms; repeat at 10-day intervals if necessary.
    - Alternatives: Carbendazim or Hexaconazole sprays.
3. Integrated Disease Management (IDM)
    - Use resistant/tolerant hybrids where available.
    - Combine cultural practices, resistant varieties, crop rotation, proper irrigation, and regular monitoring for early detection.
4. Chemical module (effective package):
    - Seed treatment with Salicylic acid (100 ppm), followed by foliar sprays of Azoxystrobin 18.2% + Difenoconazole 11.4% SC @ 0.1% (500 L/ha) applied twice, at 3 and 15 days after inoculation.

(4) *Curvularia* Leaf Spot (CLS)

Economic Importance:

Curvularia leaf spot has emerged as a serious foliar disease of maize, capable of causing yield losses of up to **60% or more** under severe conditions. With the influence of **global climate change**, the disease is now spreading to newer maize-growing regions. In India, CLS is increasingly observed across all major maize-producing areas, often in association with Maydis Leaf Blight (MLB).

Host Range: Besides maize, *C. lunata* also infects **sorghum, rice, wheat, barley, sugarcane, and many grasses**, often acting as an opportunistic pathogen.

Characteristics symptoms for identification:

- Initial symptoms appear on **lower leaves** as **small necrotic or chlorotic spots**, often surrounded by a **light-colored halo**.
- As the disease progresses, lesions spread from lower to upper leaves, typically from the **knee-high stage (30–35 days after sowing) until harvest**.
- Lesions develop into spots with a **straw-colored to light-brown center** surrounded by a **dark brown margin**, producing a clear contrast between center and edge.
- In severe infections, multiple lesions coalesce, reducing the effective leaf area and ultimately impacting grain filling and yield.

Etiology: *Curvularia lunata* (Wakker) Boedijn is primarily **airborne and polycyclic** (several infection cycles in one season).

- **Mycelium**: Septate, branched, pale to dark brown.

- **Conidiophores**: Erect, simple or occasionally branched, light brown, geniculate (bent at points of conidium formation).
- **Conidia:**
  - Typically **curved at one or more septa**, giving the fungus its name ("Curvularia").
  - Conidia are **3–5 septate**, brown in color, with the **third cell from the base usually swollen and darker** than others. Generally, **20–35 × 9–15 µm in size**.
- Stromata: Often large, erect, black, cylindrical, sometimes branched.
- Conidiogenous cells: Polytretic, integrated, terminal, somtimes later becoming intercalary sympodial, cylindrical or occasionally swollen, cicatrised.

Disease Cycle:
The causal fungus, *Curvularia lunata*, survives between cropping seasons primarily as mycelium and conidia in infected crop residues, soil, and collateral weed hosts. These structures serve as the primary source of inoculum for subsequent maize crops. Under favorable environmental conditions, particularly warm temperatures (25-35°C) and high humidity, the surviving conidia germinate and initiate infection.

Primary infection occurs when conidia, disseminated by wind currents and rain splash, land on maize leaves. The spores germinate on moist leaf surfaces and penetrate predominantly through stomata, giving rise to initial necrotic or chlorotic spots.

As the disease progresses, lesions become active sites for secondary sporulation, producing abundant conidia. These conidia are then dispersed to surrounding healthy plants, resulting in secondary cycles of infection. This polycyclic nature allows the pathogen to intensify rapidly within a single growing season, especially under prolonged periods of humidity and leaf wetness.

At the end of the cropping season, the fungus reverts to survival mode, persisting as mycelium and conidia in crop debris and alternative hosts, thereby completing the cycle and ensuring carryover to the next season.

Management
An integrated disease management (IDM) strategy is recommended:

a) **Weed Control:** Remove weeds from within and around the field, as they can act as alternate hosts for *Curvularia* and enhance disease spread.

b) **Resistant/Tolerant Varieties:** Grow resistant or tolerant hybrids (IIMRQPMH-1705 and IMHB1532) is one of the most effective preventive measures.
  - **Seed Treatment:** Treat seeds with Thiram 75 WP fungicide at 2 g/kg seeds to suppress early infection and protect seedlings.

c) **Biological and Chemical Integration**
  - Treat seeds with a **combination of *Trichoderma* chalk formulation (20 g)** plus **Mancozeb 63% or Thiram 40 FS (6 g/kg seed)** combination has been found highly effective against CLS.

(5) Pre-Flowering Stalk Rots (PrFSR)
(5a) *Fusarium* Stalk Rot (FSR)
Economic Importance:
Fusarium stalk rot is one of the most destructive stalk diseases of maize, causing yield losses of up to **42% or more** under severe conditions. In India, it is widely prevalent in **Jammu & Kashmir,**

Punjab, Haryana, Delhi, Rajasthan, Madhya Pradesh, Uttar Pradesh, Bihar, West Bengal, Andhra Pradesh, Tamil Nadu, and Karnataka.

Host Range**: Primary host**: Maize (*Zea mays*)
Also infects: rice, sorghum, wheat, banana, asparagus, and some other cereals and grasses.

Characteristics symptoms for identification:
Plants exhibit **wilting**; leaves lose their healthy green colour and turn **dull grayish-green**. The **lower portion of the stalk** changes from dark green to **straw-coloured**, with discoloration spreading upward. Roots, crown, and lower internodes may show **soft rotting and tissue decay**. On splitting the stalk, the **internal tissues display light pink to tan discoloration**, often localized near the lower internodes.

Disease generally appears **after flowering**, often progressing rapidly during grain filling. In some cases, FSR occurs in **combination with charcoal rot** (*Macrophomina phaseolina*), leading to severe damage and complicating diagnosis. Symptoms may resemble other stalk rots; hence, **laboratory confirmation** is often necessary.

Etiology:
Fusarium verticillioides (Sacc.) Nirenberg, is both a pathogen and an endophyte.

Hyphae are hyaline, septate, and branched. Conidiophores are simple, short, unbranched, arising singly; may be monophialidic (bearing a single conidiogenous cell) or polyphialidic. Microconidia (dominant type) oval to club-shaped, occasionally reniform (kidney-shaped). Size ranging 5–12 × 1.5–3 µm. Formed abundantly in long chains from monophialides on aerial conidiophores. Typically, hyaline and single-celled.

Macroconidia (rare in culture) are slender, slightly curved with nearly parallel walls and 20–55 × 2.5–4.5 µm in size. Apical cell tapered; basal cell notched or foot-shaped. Usually 3–5 septa (commonly 3). Generally, chlamydospores absent or rare in *F. verticillioides.*

Pathogen produces cell wall–degrading enzymes that facilitate host tissue invasion. Synthesizes fumonisins, particularly fumonisin B_1, which are highly toxic to plants, animals, and humans. Infection is favoured by warm and relatively dry weather conditions, especially post-flowering.

Epidemiological Factors
Disease development is favored by **warm and relatively dry conditions**. It is most severe when maize plants are exposed to **water stress after flowering**. Continuous maize cultivation and retention of infected residues also increase disease incidence. Pathogen survive as chlamydospores in crop residues and soil, contaminated seeds. Conidia spread by wind, rain splash, and insects. Warm temperatures (25-30 °C) and drought stress promote infection and fumonisin accumulation.

Disease Cycle
The fungus survives between cropping seasons in the soil and plant residues as mycelium, thick-walled chlamydospores, or sexual fruiting bodies in certain species. This survival strategy highlights the importance of crop rotation to break the disease cycle. Infection occurs when the pathogen colonizes the stalk through mycelial growth or spores, which may be produced by either sexual or asexual reproduction. Wounds or weakened tissues in the plant serve as the primary entry points for infection.

Once inside, the pathogen colonizes and feeds on the internal tissues of the internodes, often leaving the stalk hollow. As nutrients become depleted, the mycelium differentiates into chlamydospores within plant tissues, ensuring persistence. Externally, asexual spores are produced in characteristic rings around the nodes, while in some species, sexual structures and spores develop at the basal region of the stalk.

The fungus exhibits significant genetic variability due to sexual recombination and anastomosis between mycelia and asexual spores. Pathogenic strains comprise multiple isolates or races, which are often difficult to distinguish morphologically. These isolates differ in their multiplication rate, toxin production, and pigment synthesis, contributing to variation in virulence and disease expression.

Management

Integrated management practices are essential for effective control:

Sanitation and Tillage: Destroy crop debris and plough deeply during **April-May at 10-15 days intervals** to reduce survival of the pathogen.

Crop Rotation: Rotate maize with **non-cereal crops** to break the disease cycle.

Nutrient Management: Apply **balanced fertilizers** with reduced nitrogen and higher potassium to improve plant tolerance.

Irrigation Management: Avoid water stress during the **flowering stage** by providing adequate irrigation.

Resistant/Tolerant Varieties: Grow maize hybrids with resistance or tolerance to FSR, where available.

Organic Amendments & Biocontrol: Incorporate **FYM + *Trichoderma* chalk powder + vermicompost + dung ash** into soil to suppress pathogen activity.

Seed Treatment: Treat seeds with **Carbendazim** or a mixture of **Tebuconazole + *Trichoderma* chalk formulation + dung ash** to protect seedlings.

Chemical Control: Apply a foliar spray of **Carbendazim + Mancozeb** at **40 and 55 days after sowing** or immediately after symptom appearance. If disease persists, follow with a **Tebuconazole spray** at 55 days after sowing.

(5b) Bacterial Stalk Rot (BSR)

Economic Importance

Dickeya zeae is a major bacterial pathogen of maize in tropical and subtropical regions, particularly under conditions of high temperature and humidity (Saxena & Lal, 1984; Sah, 1991). It is considered one of the four major stalk diseases of maize in India, with natural incidences reaching 80-85% and yield losses up to 98.8% under artificial epiphytotic conditions. Severe outbreaks have also been reported in Brazil, where a sweet corn population during the 1979/80 rainy season was heavily infected. In temperate regions such as the USA, the disease is problematic primarily in fields under overhead irrigation.

Host range

1. *Saccharum officinarum* (sugarcane)
2. *Solanum tuberosum* (potato)

12. *Daucus carota* (carrot)
13. *Petunia hybrida*

3.	*Ananas comosus* (pineapple)	14.	*Allium fistulosum* (Welsh onion)
4.	*Zea mays* (maize)	15.	*Aechmea fasciata*
5.	*Chrysanthemum morifolium*	16.	Araceae
6.	Cyclamen	17.	*Pennisetum purpureum* (elephant grass)
7.	*Sorghum sudanense* (Sudan grass)	18.	*Musa* (banana)
8.	*Dracaena marginata* (dragon tree)	19.	*Solanum lycopersicum* (tomato)
9.	*Euphorbia pulcherrima* (poinsettia)	20.	Paspalum
10.	*Imperata cylindrica* (cogon grass)	21.	*Sorghum bicolor* (sorghum)
11.	*Ipomoea batatas* (sweet potato)	22.	*Saintpaulia ionantha* (African violet)
12.	*Megathyrsus maximus* (Guinea grass)	23.	*Urochloa mutica* (para grass)
13.	*Phalaenopsis*	24.	*Philodendron*
14.	*Oryza sativa* (rice)	25.	*Zea mays* subsp. *mays* (sweet corn

Symptoms

General onset: Symptoms typically appear 40–60 days after sowing.

Basal Rot: Initial signs include premature withering and drying of upper leaf tips, followed by lower leaves. Leaves become yellow, and basal tissues turn brown, soft, and water-soaked. The stalk interior disintegrates into a soft, pulpy mass, leading to plant lodging. A foul odor and the presence of dipterous larvae in decaying tissue are characteristic. Infection may involve one or two internodes or extend throughout the stalk, which ultimately dries and becomes a shredded fibrous mass.

Top Rot: Symptoms begin with wilting and drying of middle whorl leaves. A soft rot develops in the stalk at the base of the whorl, progressing rapidly downwards. The top of the plant droops, and the central leaf whorl can be easily pulled out, showing a rotted basal region.

Cob Rot: Infected ears initially become water-soaked and slimy, later drying up. Ears may remain undeveloped, with rotting grains covered in slime, or may completely rot, producing no viable seed.

Etiology: Pathogen responsible for causing this disease is *Dickeya zeae* (Samson et al. 2005)

Synonyms:

1. *Erwinia chrysanthemi pv. Zeae* (Sabet, 1954) Victoria et al., 1975
2. *Pectobacterium chrysanthemi* (Burkholder et al., 1953) Brenner et al., Hauben et al., 1999
3. *Pectobacterium chrysanthemi* pv. *zeae* Kelman 1974
4. Erwinia *caratovora* var. *chrysanthemi* (Burkholder et al., 1953) Dye, 1969
5. *Erwinia chrysanthemi* (Burkholder *et al*., 1953) Young *et al.*, 1978
6. *Erwinia chrysanthemi corn* pathotype Dye, 1969
7. 8 *Bacterium carotovorum f.sp. zeae* Sabet, 1954. *Erwinia maydis Kelman et al.*, 1957
9. *Pectobacterium carotovorum* var. *graminarum* Dowson & Hayward, 1960
10. *Pectobacterium carotovorum f.sp. zeae* (Sabet) Dowson, 1957
11. *Erwinia carotovora* (Jones, 1901) Bergey et al., 1923
12. *Erwinia carotovora f.sp. zeae* Sabet, 1954

Cell morphology: Gram-negative, motile, rod-shaped bacterium; 0.8-3.2×0.5-0.8 µm.

Motility: Peritrichous flagella (usually 8–11, range 3–14).

Colony characters: Produces off-white, slimy, shiny colonies on King's B medium (Kumar et al., 2015).

Epidemiology:
Favored by high temperature, high humidity, and heavy soils. In India, disease outbreaks are severe in Kharif-sown crops, particularly in Punjab (NW India), where the susceptible growth stages coincide with monsoon rainfall (August–September).

Disease severity increases with warm temperatures and frequent rains, which promote pathogen multiplication.

Disease Cycle
The bacterium is soil-borne and survives in infected crop residues. Entry occurs through natural openings (stomata, hydathodes) and through wounds in whorls, stalks, and roots caused by insects, strong winds, or mechanical damage.

Survival
In soil, *Dickeya zeae* survives for up to nine months in infected maize stalks.

In laboratory conditions, bacterial cells can be preserved in silica gel for 3 years without loss of viability. However, under field conditions, virulence generally persists for only a single crop season.

Dispersal
Spread occurs via rainwater, surface runoff, and irrigation. Insects such as the maize borer facilitate initial infection and subsequent spread.

a) Cultural Practices
Crop rotation: Rotate maize with non-host crops (legumes, oilseeds, vegetables) to minimize soil inoculum build-up.

Field sanitation: Remove and destroy infected plant debris to reduce survival of the bacterium.

Avoid waterlogging: Ensure proper drainage, as high soil moisture and standing water promote disease development.

Adjust planting time: Avoid sowing maize during periods that coincide with peak monsoon rains in endemic areas.

Optimum plant spacing: Maintain adequate spacing to improve aeration and reduce humidity within the crop canopy.

b) Host Resistance:
Cultivate resistant or tolerant hybrids, where available, to reduce susceptibility. Screening and adoption of locally recommended varieties is crucial in endemic zones.

c) Irrigation Management
- Use furrow or drip irrigation instead of overhead irrigation, which enhances bacterial spread.
- Avoid frequent flooding, particularly during warm and humid weather

d) Nutrient and Crop Management
Apply balanced fertilizers, with sufficient potassium to improve stalk strength and disease tolerance. Avoid excessive nitrogen, as lush growth predisposes plants to infection.

e) Seed and Soil Treatment

- Treat seeds with biocontrol agents such as *Trichoderma harzianum* or *Pseudomonas fluorescens* formulations to suppress pathogen populations in the rhizosphere.
- Application of FYM (farmyard manure) enriched with biocontrol agents can improve soil microbial balance and reduce pathogen survival.

f) Chemical Control

In early stages of infection, foliar sprays or whorl application of streptocycline (100-200 ppm) or copper-based fungicides (e.g., copper oxychloride @ 0.25%) may suppress disease spread. Soil drenching around infected plants with streptocycline + copper formulations has shown effectiveness in reducing disease incidence.

5c) Pythium Stalk Rot (PSR)

Economic Importance:

Pythium stalk rot is generally confined to hot and humid maize-growing regions, particularly where soils are poorly drained. Fields located in valleys and river bottoms are especially prone to infection. Damage is usually localized within a field, although in some cases, entire patches may lodge prematurely. However, widespread destruction is uncommon, as the natural dispersal of the pathogen is limited.

Host range

Pythium aphanidermatum is known to infect a wide range of cultivate crops, including cereals and grassess, cucurbits, horticultural crops, and cotton.

Symptoms

Infection is typically restricted to the first internode above the soil surface. The stalk becomes soft, water-soaked, darkened, and collapsed. Affected stalk tissues rot, often causing the stalk to twist and lodge, though complete breakage is rare.

Despite infection, plants may appear healthy for extended periods since the vascular bundles often remain intact for some time. Disease may occur even before flowering, reducing plant vigor and yield potential.

Causal organism: Pythium aphanidermatum (Edson) Fitzp., 1923

Synonyms:

1. *Rheosporangium aphanidermatum* Edson, 1915
2. *Nematosporangium aphanidermatum* (Edson) Fitzp., 1923
3. *Pythium butleri* Subraman., 1919
4. *Nematosporangium aphanidermatum* var. *hawaiiensis* Sideris, 1931

Morphological Identification of *Pythium aphanidermatum*

Hyphae: Non-septate, hyaline.
Sporangia: Inflated (balloon-like), branched or unbranched.
Zoospores: Kidney-shaped, laterally biciliate; approximately 7.5 × 12 µm.
Oogonia: Spherical, 22–27 µm in diameter, borne on straight stalks.
Antheridia: Intercalary.
Oospores: Thick-walled, 17–19 µm in diameter; typically observed in infected stalk tissues.

Epidemiology

The disease is favored by poorly drained, waterlogged soils with high humidity. It is most common in low-lying or river-bottom fields. High temperatures (25-35°C), dense plant populations, and excessive nitrogen fertilization further increase disease incidence and severity.

Disease Cycle

Pythium aphanidermatum survives in the soil either as mycelium or oospores. The thick-walled oospores can persist in the soil for several years, serving as the primary survival and infection structures. Under congenial weather conditions, oospores germinate to produce sporangia, which in turn release motile zoospores.

The zoospores are chemotactically attracted to host root and stalk tissues by plant exudates that act as nutrient or stimulatory signals. They swim in free water present at or just below the soil surface and initiate infection, leading to the formation of characteristic water-soaked lesions.

Within the infected host tissues, the pathogen produces oogonia and antheridia, representing the sexual stage of its life cycle. Fertilization of the oogonium by the antheridium results in the formation of new oospores, which enable long-term survival in soil and crop debris.

The pathogen spreads primarily through the movement of contaminated soil, infected residues, irrigation water, or flooding, which facilitates the transport of oospores and the motility of zoospores. Under hot, humid, and poorly drained conditions, the cycle repeats rapidly, causing localized epidemics of stalk rot.

Management of *Pythium aphanidermatum*

a) Cultural Practices

- Field sanitation: Remove and destroy infected crop residues to reduce the source of oospores and mycelial inoculum.
- Crop rotation: Adopt rotation with non-host crops (e.g., legumes, oilseeds) to reduce soil inoculum buildup.
- Drainage improvement: Avoid water stagnation by maintaining proper field drainage, especially in valley and river-bottom fields.
- Optimum plant density: Prevent excessive plant population to improve aeration and reduce humidity at the base of plants.
- Balanced fertilization: Avoid excessive nitrogen; integrate with adequate potassium to strengthen stalk tissues against infection.

b) Resistant/Tolerant Varieties

Cultivation of resistant or tolerant maize hybrids (eg. Ganga and Safed 2 etc.) is recommended where available, as host resistance provides a sustainable management option.

c) Biological Control

Application of biocontrol agents such as *Trichoderma harzianum*, *T. viride*, or *Pseudomonas fluorescens* in soil or as seed treatment can suppress *Pythium* propagules and enhance soil suppressiveness.

d) Chemical Management

Seed treatment: Treat seeds with systemic fungicides such as Metalaxyl, Metalaxyl-M, or combinations (e.g., Metalaxyl + Mancozeb at 2–3 g/kg seed) to protect seedlings from early infection.

Soil drenching: In severely affected fields, drenching with systemic fungicides such as Ridomil Gold (Metalaxyl + Mancozeb) may help reduce primary inoculum in the root zone.

(6) *Polysora* Rust / Southern Corn Rust

Economic Importance:

Polysora rust, commonly known as southern rust of maize, is one of the most important rust diseases in tropical and subtropical maize-growing regions worldwide. Unlike common rust, it thrives under warm climatic conditions, making it particularly severe in tropical areas. In some temperate regions, during seasons characterized by unusually warm weather, the disease may also emerge as a significant production constraint. Yield losses of over 45% have been reported under epidemic conditions, marking it as a serious threat to maize production.

Host Range

This rust primarily affects members of the Poaceae family, including Themeda (kangaroo grass), *Tripsacum dactyloides* (eastern gamagrass, USA), and cultivated as well as wild forms of maize (*Zea mays, Zea mays* subsp. *mays* – sweet corn, and *Zea mays* subsp. *mexicana – teosinte*).

Symptoms

Small, circular to oval pustules measuring 0.2–2 mm in length. Pustules are lighter in color compared to those of common rust, appearing orange-red to light cinnamon brown. They are typically more numerous on the upper leaf surface, but appear more slowly and less abundantly on the lower leaf surface. Initially, pustules are less powdery than those of common corn rust. The leaf epidermis remains intact for an extended period, covering the pustules, and later splits open through a longitudinal slit.

In advanced stages, teliospores develop, appearing chocolate brown to black, often forming a ring around the uredial pustules late in the season.

Etiology: Pathogen responsible for causing this disease is Puccinia *polysora* Underw., 1897

Teliomorph: *Dicaeoma polysorum* (Underw.) Arthur, 1906

Only uredial and telial stages of *Puccinia polysora* have been observed.

Uredinia: Small, circular to oval, cinnamon-brown pustules, uniformly distributed on the leaf surface.

Urediniospores: Yellowish to golden brown, ellipsoid, echinulate, with 4–5 equatorial pores; measuring 26–41×18.5–30 µm. Each uredinium may release up to 220 spores per day, particularly from early June to mid-August.

Teliospores: Typically, bicellular, dark red in color, measuring 26-50 × 16-27 µm. Although teliospores are produced, they remain enclosed within the epidermis and are generally non-germinating, thus considered unimportant in the epidemiology of the disease.

Epidemiological Factors

Development of *polysora* rust is favored by warm and humid conditions, with an optimal temperature range of 24-28°C for urediniospore germination and infection. Extended periods of dew or high relative humidity, which are essential for spore germination and penetration.

Late-planted and late-maturing maize, which remains susceptible during periods of high inoculum pressure. In temperate regions, the disease is more common towards the end of the growing season when temperatures rise.

Disease Cycle
The disease is initiated by wind-dispersed urediniospores, which originate from previously infected maize plants. Spores are carried progressively northward during the cropping season, leading to fresh infections. Upon deposition on leaf surfaces, urediniospores require free water (dew or rainfall) for germination. Germ tubes penetrate primarily through stomata.

Symptoms appear 3-6 days after infection, and by 7-10 days, pustules rupture to release new urediniospores, perpetuating the secondary infection cycle. Teliospores, although formed later in the season, do not rupture the epidermis and remain epidemiologically insignificant. Disease progress is most rapid under high temperatures (25-28°C), high humidity, and heavy rainfall in fields planted with susceptible maize cultivars.

Management
Adjusting Planting Time
Early sowing is recommended so that the crop establishes and matures before the peak infection period. Conversely, late planting should be avoided, as it increases the risk of severe *Polysora* rust incidence.

Crop Rotation
Rotation with non-cereal crops helps disrupt the disease cycle, lowers inoculum carryover in the soil, and reduces the likelihood of disease recurrence.

Field Sanitation
Removal and destruction of infected crop residues are essential to minimize the survival of the pathogen between seasons and to reduce primary inoculum sources.

Resistant/Tolerant Hybrids
The use of resistant or tolerant maize hybrids is one of the most effective and sustainable management strategies. Farmers should select hybrids recommended for their specific region to achieve maximum protection.

Chemical Control
When symptoms appear, particularly the development of uredial pustules, fungicidal sprays can be employed to suppress further spread. Spraying Mancozeb at 2-3 g/L of water, applied twice at 15-day intervals, is recommended for effective control.

7. Rajasthan Downy Mildew (RDM)
Economic Importance:
Rajasthan downy mildew was first reported from northern India in 1968 at the Regional Research Station, Vallabh Nagar, Udaipur (Rajasthan). The disease causes severe yield losses under favorable conditions, particularly when infection occurs at the early crop stages (2-3 leaf stage). Following infection, the disease spreads rapidly and affects large plant populations. Systemically infected plants often produce rudimentary cobs which are unsuitable for grain harvest, leading to complete yield loss in severe cases. Epidemics of RDM have been identified as a serious production constraint in several maize-growing regions of India.

Symptoms
Typical symptom: “Half diseased leaf”, where the base of the second and third leaves becomes pale, contrasting with the healthy green portion. Yellow stripes often extend from the base upwards into the green region of the leaf. Severely affected fields exhibit a generalized yellowish appearance, visible from a distance.

Most infected plants wilt and die by the knee-high stage. Under humid conditions, whitish fluffy fungal growth is visible on both upper and lower leaf surfaces due to profuse sporulation. Infected leaves may become yellow, erect, and closely set on the stem.

Systemically infected plants fail to form cobs; if cobs develop, they are small, poorly filled, and sterile (no pollen production in tassels). Infected plants exhibit weak stems, poor root growth, but no malformation or excessive tillering.

Etiology of the Pathogen

Pernosclerospora heteropogoni

Conidiophores: Macronematous, determinate, dichotomously branched with a swollen base; measuring 81.6-142.8 × 14.3-25.5 µm (average 101.8 × 20.1 µm).

Conidia: Globose, hyaline, thin-walled; 14.3-22.4 × 14.3-20.4 µm (average 17.7 × 16.2 µm). Produced nocturnally on both *Heteropogon contortus* and maize leaves; germinate readily via germ tubes.

Oospores: Spherical with a persistent oogonial wall; measuring 24.5-29 µm. Abundant in *H. contortus* but absent on maize.

Epidemiological Factors: Inoculum density strongly influences disease severity. Experimental inoculations revealed that 6000 conidia/ml can induce 80% disease incidence (Rathore, 1983; Rathore & Siradhana, 1987b). Temperature and moisture play critical roles: maximum infection occurs at 23-25°C, with high rainfall (154 mm) and relative humidity 87%. Conidia germinate between 10-35°C, optimally at 25°C, but fail to germinate above 40°C.

Disease Cycle

The collateral host, *Heteropogon contortus*, plays a key role in the disease cycle. This annual grass harbors abundant mycelium and oospores in its roots, serving as the primary inoculum source.

Primary infection: Oospores infect *H. contortus* seedlings and subsequently maize seedlings (23 leaf stage).

Secondary infection: Abundant nocturnal conidia produced on infected maize leaves facilitate rapid disease spread within and between fields.

Survival: Oospores produced late in the *H. contortus* growing season persist in soil and plant residues, ensuring pathogen carryover to the following season. Symptoms: Pale leaf bases ('half diseased leaf'), yellow stripes, whitish downy growth under humid conditions.

Management

1. Cultural Practices:
   - Crop rotation: Rotate maize with non-host crops (legumes, oilseeds, vegetables) to reduce oospore build-up in soil.
   - Field sanitation: Remove and destroy infected plant debris and collateral hosts such as *Heteropogon contortus* to limit survival of the pathogen.
   - Avoid continuous maize cultivation in endemic areas.
   - Early sowing: Establishing the crop early helps escape peak infection periods.

2. Host Resistance:

Use resistant or tolerant hybrids/varieties wherever available. Breeding for resistance remains the most economical and eco-friendly management approach.

3. Seed Treatment:

Treat seeds with systemic fungicides such as: Metalaxyl @ 6 g/kg seed or Metalaxyl + Mancozeb mixtures. These suppress primary infection by eliminating seed-borne inoculum and provide protection to emerging seedlings.

4. Chemical Control (Foliar Application)

In areas with high disease pressure, apply foliar sprays of fungicides such as Metalaxyl + Mancozeb (0.25%) at 10-12-day intervals after the appearance of initial symptoms to reduce secondary spread.

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DRAGON FRUIT: A CLIMATE-RESILIENT CROP FOR DIVERSIFIED HORTICULTURE

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Abstract

Dragon fruit, also known as pitaya, strawberry pear (*Hylocereus spp*. and *Selenicereus spp*.), or *Kamalam*, is rapidly emerging as a high-potential crop across the globe. Its popularity among Indian farmers has grown due to several advantages, including low water and nutrient requirements, comparatively fewer resources needed for orchard establishment and upkeep, the possibility of multiple harvests annually, sustained productivity for up to two decades, and a favorable benefit–cost ratio. Among consumers, the fruit has gained preference owing to its rich nutraceutical and functional properties, particularly its high antioxidant and fiber content. Being a crassulacean acid metabolism (CAM) plant with xerophytic traits, dragon fruit can thrive under diverse agro-climatic conditions and on marginal lands, making it a low-maintenance yet highly profitable crop. In India, its cultivation is expanding steadily in states such as Maharashtra, Karnataka, Andhra Pradesh, West Bengal, Telangana, Tamil Nadu, Odisha, Gujarat, the Andaman and Nicobar Islands, and several northeastern regions. However, a key challenge remains the development of region-specific protocols for cultivation, harvesting, and post-harvest handling to improve productivity and fruit quality. Currently, limited scientific information is available on its cultivation practices. Comprehensive research on production techniques, global and national cultivation trends, and the health-promoting attributes of dragon fruit will play a crucial role in maximizing returns for growers and consumers while facilitating market expansion.

Keywords: Dragon fruit, health benefits, cultivation

Introduction

Dragon fruit (*Hylocereus* spp.), commonly referred to as red pitaya or *Kamalam*, is a perennial, climbing cactus gaining widespread attention owing to its striking red or pink hue, premium market value, and rich array of nutrients including antioxidants, vitamins, and minerals. Native to Central and South America, this exotic fruit was introduced to India in the late 1990s.

The advantages of cultivating dragon fruit are compelling: it thrives on comparatively low water and nutrient inputs, requires moderate investment for orchard establishment, allows multiple harvests annually, continues to yield over long spans (up to two decades), and offers an attractive benefit-to-cost ratio. Early data indicate India's production reached approximately 4.2 metric tonnes from about 400 hectares, achieving yields of 8–10.5 t/ha (Ahmad et al., 2019).

Since the early 2000s, cultivation has seen significant growth. By 2020, the area under cultivation expanded dramatically from minimal coverage in 1990 to over 3,000 ha, producing around 12,000 MT with an average productivity of approximately 12.9 t/ha. Major producer states include Gujarat, Karnataka, and Maharashtra together accounting for about 70 per cent of overall production. For instance, Gujarat cultivated around 1,214 ha yielding 4,079 MT; Karnataka contributed 485 ha producing 2,369 MT; and Maharashtra added 323 ha yielding 1,677 MT. Other notable growing regions include West Bengal, Tamil Nadu, Andhra Pradesh, Telangana, Odisha, and the Andaman and Nicobar Islands.

The northward expansion of dragon fruit cultivation is gaining momentum. In Uttar Pradesh, Mirzapur has emerged as a significant hub with cultivation now exceeding 260 ha. The state government is establishing a Centre of Excellence to support production, marketing, and farmer training. Likewise, the Prayagraj region is witnessing growing adoption of dragon fruit cultivation, driven by reduced rainfall, low water needs, and government subsidies under the UP-AGREES initiative farmers there benefit from 40 per cent subsidies and up to ₹2.78 lakh per hectare support.

Meanwhile, Odisha's Balangir district has made strides in exports-dragon fruit consignments totalling 330 kg were successfully sent to Dubai, fetching Rs 300/kg (a 20% price increase year-over-year), showcasing improvements in fruit quality and growing international demand.

Dragon fruit, a member of the cactus family, thrives best under long-day conditions that promote flowering. It is well suited for cultivation in the agro-climatic zones of Southern, Western, and Northeastern India. A dry, frost-free climate is considered most favourable for its growth and productivity. Among the Indian states, Gujarat, Karnataka, and Maharashtra have emerged as the leading producers, together accounting for nearly 70% of the country's total dragon fruit output.

Health Benefits of Dragon Fruit

Dragon fruit is a nutrient-dense fruit, packed with vitamins, minerals, phenolic compounds, flavonoids, antioxidants, and dietary fibers, which collectively contribute to numerous health benefits. Its high vitamin C content not only boosts immunity but also promotes faster healing of cuts and wounds, while offering relief in conditions such as cough and asthma. Traditionally, it has also been used to help manage uterine haemorrhage.

Regular consumption of dragon fruit is associated with improved cardiovascular health and better regulation of blood sugar levels, particularly beneficial for individuals with type 2 diabetes. Being a rich source of calcium and phosphorus, it supports the development of healthy tissues, strengthens bones, and contributes to strong teeth. These properties make dragon fruit both a functional food and a valuable addition to a balanced diet.

The international market recognizes four main varieties:

Variety	Skin	Flesh	Major Suppliers
Hylocereus undatus	Red	White	Vietnam, Thailand
Hylocereus polyrhizus	Red	Red	Malaysia, Israel
Hylocereus costaricensis	Red	Purple	Ecuador, Guatemala
Selenicereus megalanthus	Yellow	White	Colombia, Ecuador

The global dragon fruit market is projected to grow at a CAGR of 3.7 per cent over the next five years due to its increasing popularity as a functional superfruit with antioxidant and fiber-rich properties.

Fig. 1: Four different types of dragon fruit in world market

The red–skin with white flesh, red–skin with red flesh, and red–skin with purple flesh and yellow–skin with white flesh accounts approximately 94, 4.0, 1.5 and 0.5 per cent shares in world market.

Soil and Climate

Dragon fruit can be cultivated in a wide variety of soil types; however, well-drained soils rich in organic matter with slightly acidic conditions are considered ideal for its growth. The crop adapts well to the climatic conditions of several Indian states, including Karnataka, Kerala, Tamil Nadu, Maharashtra, Gujarat, Odisha, West Bengal, Andhra Pradesh, and the Andaman & Nicobar Islands. Its ability to tolerate adverse weather makes it suitable for diverse agro-climatic zones.

The crop requires an annual rainfall ranging from 1,145 to 2,540 mm. A dry tropical climate with an optimum temperature of 20–29 °C is most favourable for its cultivation. While dragon fruit plants can withstand short periods of extreme conditions up to 38-40 °C on the higher side and around 0 °C on the lower side temperatures above 40 °C can cause significant plant damage. Additionally, heavy rainfall often leads to flower and fruit drop, which remains a common challenge in cultivation (Karunakaran et al., 2014; Karunakaran & Arivalagan, 2019).

Propagation and Planting

Dragon fruit can be propagated either through seeds or stem cuttings. While both methods are possible, commercial cultivation predominantly relies on stem cuttings, as seed propagation often results in high variability and requires 3-4 years to bear fruit. Stem cuttings are prepared from healthy, high-yielding mother plants after the fruiting season.

For planting, 20-25 cm long cuttings are typically used. These are collected 1-2 days before field planting to allow the cut ends to dry and reduce latex exudation. Prior to planting, cuttings should be treated with fungicides to prevent fungal infections. They are usually placed in polybags filled with a growing medium of soil, farmyard manure, and sand in a 1:1:1 ratio, and kept under partial shade. Within 5-6 months, the cuttings develop strong roots and become suitable for field planting (Tripathi et al., 2014).

Dragon fruit performs best in open, sunny areas, as shade negatively affects flowering and fruiting. The spacing of plants depends on the type of support system adopted for training. Under a vertical support system, a spacing of 1.5-2.0 meters is recommended, while a horizontal trellis system requires closer spacing of about 50 cm, which enables high-density planting. With intensive methods, more than 1,700 plants can be accommodated per acre, significantly enhancing productivity.

Training System

Dragon fruit plants are vigorous climbers, capable of growing up to 8 cm per week; therefore, adopting a proper training system is crucial for effective canopy management and higher yields. During the initial growth phase, lateral buds and side branches are pruned to encourage the main stem to grow vertically along the support structure. Once the vine reaches the top of the pole, lateral branches are allowed to develop. Pruning the tip of the main stem at this stage stimulates the emergence of lateral shoots around the ring, which then spread outward to form an umbrella-shaped canopy. This umbrella-like structure is the primary site for flower initiation and fruit development.

Different trellis systems are used to train dragon fruit plants, including concrete poles with rings, T-stands, iron wire supports, and wooden ladders. Among these, concrete poles are widely preferred due to their durability and ability to withstand long-term orchard conditions. Under vertical support systems, a spacing of 2-3 meters between rows is recommended. Typically, three cuttings are planted per support, which allows accommodation of about 2,000 to 3,750 cuttings per hectare, depending on the planting density.

Water and Nutrient Management

Irrigation and fertigation practices in dragon fruit cultivation should be tailored according to soil type and prevailing climatic conditions. On average, applying 2-4 liters of water per plant twice a week is adequate, though in dryland regions, drip irrigation is highly recommended as a sustainable and efficient method.

Dragon fruit has a shallow root system that enables it to quickly absorb available nutrients, even in small quantities. Hence, balanced nutrition plays a vital role in ensuring plant health, yield, and fruit quality. A combination of organic manures and mineral fertilizers is considered most effective. For optimum performance, an application of approximately 450 g nitrogen (N), 300 g phosphorus (P_2O_5), and 350 g potassium (K_2O) per plant has been reported to give the best results in terms of yield and fruit quality.

Pests and Diseases

Dragon fruit in India is affected by several insect pests and diseases that can significantly reduce yield and quality. Common pests include ants, nematodes, scale insects, and mealybugs. Among these, ants are particularly destructive, as they damage flowers and developing fruits, often leading to substantial economic losses.

In addition to pests, dragon fruit is susceptible to various diseases of fungal, viral, and bacterial origin. Major fungal pathogens include *Gloeosporium agaves*, *Macssonina agaves*, *Dothiorella* sp., and *Botryosphaeria dothidea*, which can cause stem and fruit rots. Viral diseases such as *Cactus* *virus X* have been reported, leading to stunted growth and reduced vigor. Bacterial infections caused by *Xanthomonas* sp. and *Erwinia* sp. may result in soft rots and tissue damage (Guyen, 1996).

Harvesting

Dragon fruit reaches maturity relatively late in its growth cycle, with visible changes in skin color serving as an indicator of ripeness. After anthesis, the fruit skin transitions from green to red or rosy pink within 25–27 days (Nerd et al., 1999). In the case of *Hylocereus costaricensis*, the fruit generally requires about 30 days to attain harvest maturity.

Harvesting can be slightly challenging due to the absence of a distinct peduncle. Currently, the recommended technique involves gently twisting the fruit in a clockwise direction, which allows easy detachment with minimal or no injury. Post-harvest handling must be done carefully, particularly for *H. costaricensis*, as its foliated scales are delicate and prone to breakage during processing and storage.

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