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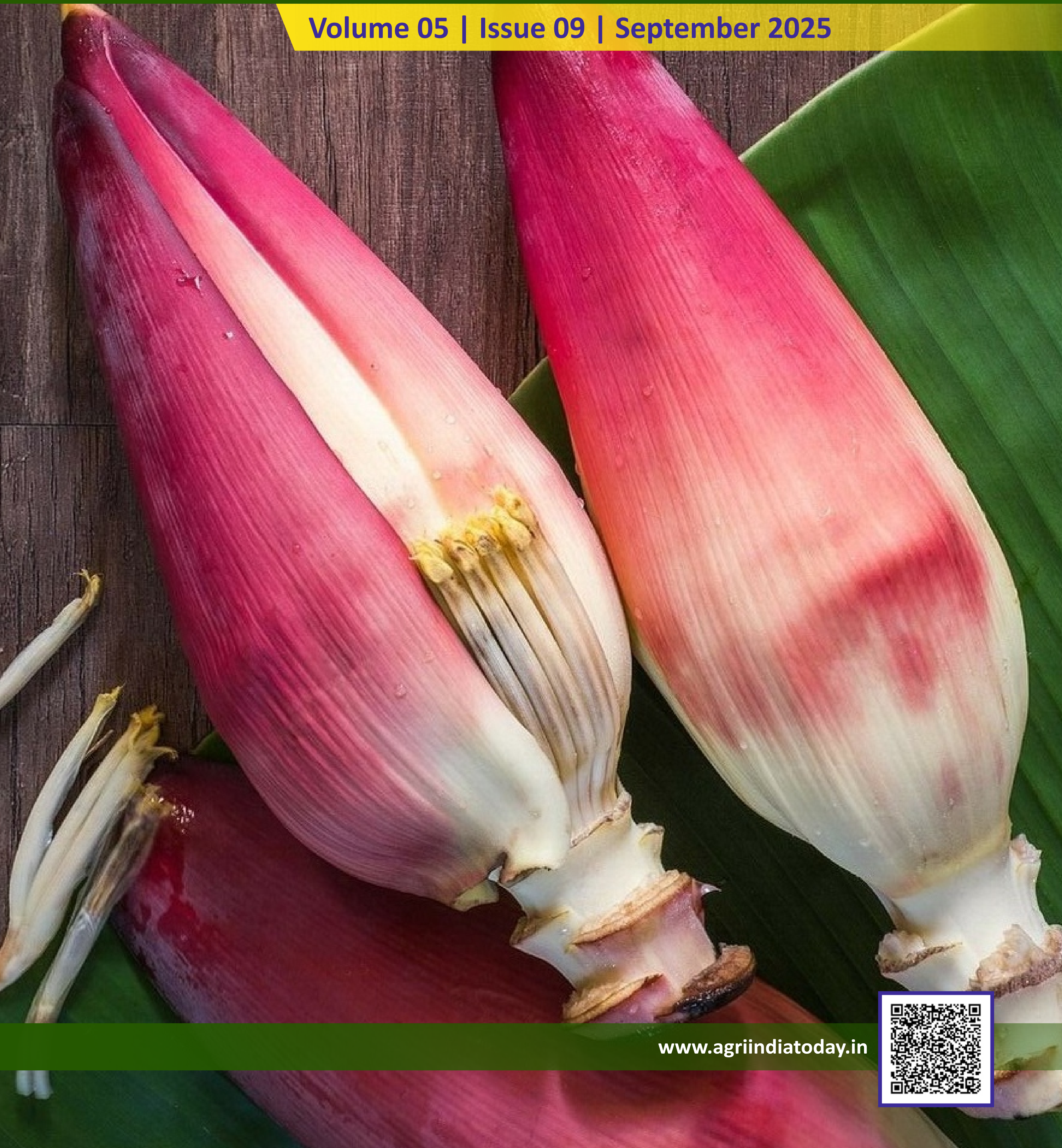

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AGRO-TEXTILES: A SUSTAINABLE APPROACH TO MODERN AGRICULTURE

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Abstract
Agro-textiles are specially designed technical textiles that support modern agriculture by protecting crops and enhancing productivity. Made from natural or synthetic fibers, they are used in shade nets, insect-proof fabrics, mulching mats, ground covers, and erosion control materials. These applications help conserve soil and water, reduce pesticide use, and safeguard crops from pests and climatic stresses such as wind, frost, and excessive sunlight. By creating favourable microclimatic conditions, agro-textiles improve crop yield, quality, and post-harvest management. With growing concerns over food security and sustainable farming, agro-textiles present significant opportunities, particularly with innovations in biodegradable materials and smart textile technologies for resource-efficient agriculture.

Key Words: Agro textiles, Crop protection, shade net, protected cultivation

Introduction

Agriculture today faces multiple challenges such as climate change, pest attacks, excessive solar radiation, and depletion of natural resources. To overcome these issues, agro-textiles have emerged as an innovative solution. Agro-textiles are specially designed woven, nonwoven, or knitted fabrics used in agriculture, horticulture, forestry, and aquaculture. They help in modifying crop microclimate, conserving resources, and protecting plants from biotic and abiotic stresses.

These technical textiles are typically manufactured from synthetic polymers such as polypropylene, polyethylene, polyester, and nylon, often with UV stabilizers to ensure durability under outdoor conditions.

Types of Agro-Textiles and Their Applications

i. Sunscreen (Shade) Nets

Sun screen nets are woven or knitted nets made of UV-stabilized polyethylene used to protect crops from excessive solar radiation, reduce temperature, and prevent leaf scorching.

- Widely used in nurseries, polyhouses, and for high-value crops like capsicum, tomatoes, orchids, and roses.
- Enhance photosynthesis efficiency, improve crop quality, and extend the growing season.

ii. Bird Protection Nets

Bird Protection nets are lightweight, durable nets that act as a physical barrier against birds used to protect vineyards, orchards, and vegetable fields from bird damage.

- Used in grape farms to prevent damage from parrots and starlings; mango orchards also use them during ripening.
- Reduces economic losses while being eco-friendly compared to chemical repellents.

iii. Bird Cover Nets

Bird Cover nets are fine mesh fabric used to cover individual trees or small plots to protect fruit-bearing trees (e.g., guava, papaya, litchi) during fruit ripening.

- Cost-effective for small-scale farmers and reduces the need for scare tactics.

iv. Ground Covers (Mulch Mats)

Ground cover nets are oven or nonwoven fabrics placed directly on soil surface used to control weed growth, prevent soil erosion, conserve soil moisture, and maintain soil temperature.

- Used in vegetable cultivation, strawberry farming, and landscape gardening.
- Reduces dependence on herbicides and improves water-use efficiency.

v. Insect Nets

Insect nets are fine mesh nets that restrict insect entry without using pesticides used in polyhouses and open fields to protect crops from aphids, whiteflies, and fruit flies.

- Widely adopted in cucumber, tomato, and capsicum cultivation.
- Reduces pesticide usage and enhances safe food production.

vi. Mulching Films

Mulching films are thin plastic films, often black or silver, spread over the soil used to conserve moisture, suppress weeds, and protect soil from erosion.

- Commonly used in watermelon, muskmelon, and strawberry cultivation.
- Improves crop yield and reduces irrigation frequency.

Advantages of Agro-Textiles

- Protect crops from UV radiation, wind, hail, and excess rain.
- Reduce post-harvest losses by preventing damage from birds and insects.
- Improve soil health and water retention through mulches and ground covers.
- Contribute to pesticide reduction, supporting eco-friendly farming.
- Provide controlled environment farming, enhancing yield and quality.

Conclusion

Agro-textiles are transforming modern agriculture by combining textile engineering with crop science. From shade nets that control sunlight to ground covers that suppress weeds, and bird nets that reduce crop losses, these innovations offer sustainable and cost-effective solutions. With growing emphasis on climate-resilient and eco-friendly agriculture, the role of agro-textiles will continue to expand globally.

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AQUAMIMICRY IN SHRIMP AQUACULTURE: A SUSTAINABLE SYNBIOTIC APPROACH USING COPEFLOC TECHNOLOGY

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Introduction

Aquamimicry is a sustainable shrimp farming method developed in Thailand that mimics natural aquatic ecosystems. It creates a natural food chain in the pond by promoting the growth of zooplankton (like copepods) and beneficial bacteria. Instead of using expensive commercial feed, farmers use low-cost carbon sources such as rice bran, wheat bran, or soybean meal. These carbon sources are fermented by probiotics like *Bacillus* species, which improve water quality and help grow nutritious live food for the shrimp. This natural system reduces the need for antibiotics, maintains clean water, and enhances shrimp immunity and growth.

Unlike traditional methods, aquamimicry relies on natural processes to support shrimp health and minimize environmental impact. It involves minimal water exchange, reduces disease outbreaks, and improves feed efficiency. Compared to biofloc systems, aquamimicry is less dependent on managing nitrogen levels and includes the regular removal and reuse of pond sediment. By combining prebiotics (like rice bran) and probiotics, aquamimicry forms a "synbiotic" system that supports both the shrimp and the pond ecosystem, offering a low-cost and eco-friendly alternative for shrimp farming.

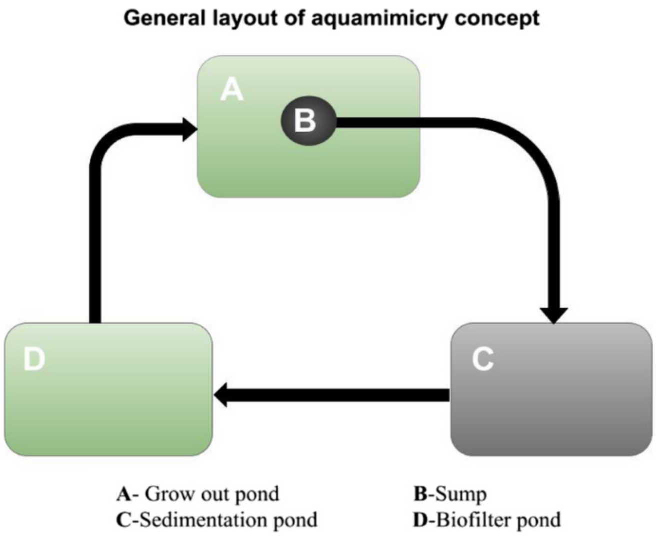

Figure 1 : Aquamimicry General Layout

Procedure

Step I : Pond Preparation

- Filter seawater using 200–300 µm filter bags and pump into the culture pond.
- Add probiotics such as *Bacillus* spp. to the water.
- Gently drag pond bottom daily for one week to:
    - Prevent biofilm formation.

    - Mix probiotics into the soil.
- Add fermented rice bran or wheat bran (50–100 mg/L) to:
    - Promote zooplankton blooms.
    - Remove aquatic weeds (use 20 ml/L).
- Provide strong aeration to:
    - Mix nutrients and probiotics evenly.
    - Reduce harmful effects of tea seed cake.

Step II: Carbon Source Preparation & Application

- Mix huskless rice/wheat bran with water in a 1:5 to 1:10 ratio.
- Add probiotics and aerate the mixture for 24 hours.
- Use the upper crumbled layer of the fermented mix in the pond.
- Maintain the pH of the mixture around 6.

Step III: Post-Larvae (PL) Stocking & Pond Management

- Stock shrimp post-larvae (PL) at 30–40 per m^2 (12–15 PL total).
- Apply fermented carbon source:
    - 1.0 ml/L for extensive culture.
    - 2.0–4.0 ml/L for intensive culture (based on water turbidity of 30–40 cm).
- Gently drag pond bottom every two weeks after stocking.
- Add probiotics monthly:
    - 1–5 ml/L (liquid) or
    - 1–10 g/m^3 (powder) depending on shrimp density and water conditions.
- Remove extra silt from the sedimentation pond using a central drainage system (2.0 m sides, 4.0 m center).
- Monitor water quality daily, especially 2 hours post-feeding to prevent anaerobic conditions and *Vibrio* outbreaks.
- Optionally stock milkfish or catfish in low density to:
    - Consume excess plankton and detritus.
    - Provide additional income.

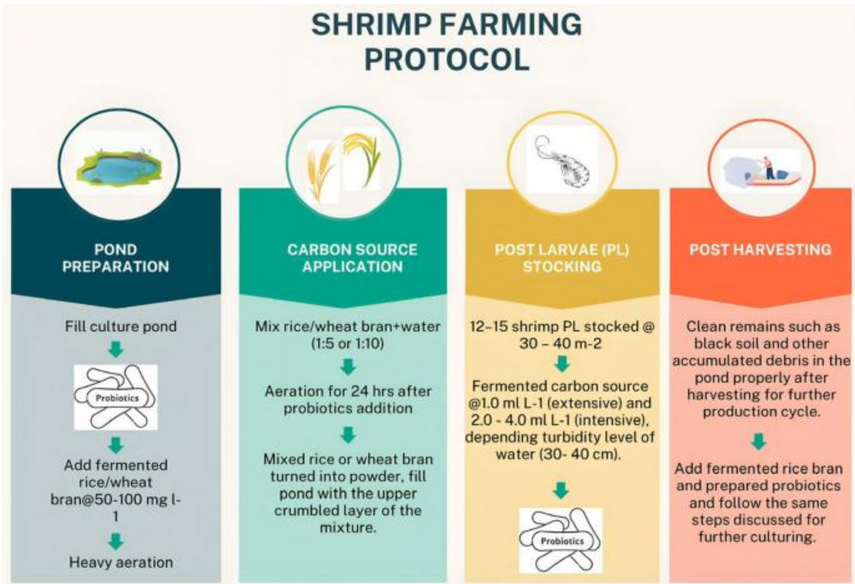

Figure 2: Aquamimicry Shrimp Farming

Step IV: Post-Harvest Management

- Thoroughly clean the pond after harvesting:
  - Remove black soil and leftover debris.
- Restart the cycle:
  - Add fermented rice bran and probiotics.
  - Repeat the earlier steps for the next production cycle.
- Maintain good hygiene and pond management to prevent disease or pathogen development.

Technique for Preparing Fermented Rice Bran

- **Ingredients Used:**
  - Powdered **huskless rice bran** or **wheat bran**
  - **Probiotics** (e.g., *Bacillus* spp.)
  - **Hydrolyzing enzymes**
  - **Water**
- **Preparation Steps:**
  - Mix powdered rice bran with water.
  - Add probiotics and hydrolyzing enzymes.
  - Maintain a water-to-bran ratio (commonly 1:5 to 1:10).
  - Let the mixture **ferment for 24 hours** (anaerobic condition preferred).
  - Maintain pH at around **6.0** during fermentation.
  - After fermentation, apply at a rate of **500–1000 kg/ha** or **1.0 ml/L** during the rearing phase.
  - Use the fermented mix before **post-larvae (PL) stocking** to trigger **zooplankton (copepod) blooms**.

Benefits & Importance of Fermented Rice Bran in Aquamimicry

- Acts as a **carbon source**, **prebiotic**, and part of a **synbiotic system** (when combined with probiotics).
- Stimulates **copepod growth** (natural shrimp feed) within a week of application.
- Enhances **shrimp digestion**, **growth**, and **survival rates**.
- Boosts the **nutritional value**:
  - Protein: ~16.79%
  - Fat: ~14.92%
  - Carbohydrates: ~50.94%
  - Ash: ~17.36%
- Reduces **anti-nutritional factors (ANFs)** like phytic acid, fiber, and toxins.
- Fermentation converts carbohydrates to **microbial proteins**, improving **amino acid** and **vitamin** content.
- Substitutes part of fishmeal in shrimp feed, **reducing costs**.
- Helps reduce harmful bacteria like **Vibrio sp.** and increases beneficial ones like **Bacillus sp.**
- Improves enzyme activities in shrimp gut (e.g., **trypsin**, **fibrinolytic enzymes**), aiding digestion.
- Increases water quality and prevents disease outbreaks in shrimp ponds.

Application of Probiotics in Aquamimicry

Probiotics are live beneficial bacteria that, when added through feed or water, enhance the gut health, growth, and immunity of cultured aquatic species while also improving the overall aquaculture environment. They help maintain gut microbiota, inhibit harmful bacteria, and disrupt quorum sensing, which prevents biofilm formation and reduces virulence. During fermentation, probiotics release enzymes that lower stomach pH and reduce toxic compounds. Species like *Bacillus sp.* and *B. subtilis* are commonly used due to their stability, ability to produce essential vitamins (e.g., B1, B12), and effectiveness in promoting beneficial gut microbes. In aquamimicry systems, probiotics work synergistically with fermented carbon sources to form synbiotics, aiding in zooplankton growth, improving feed conversion ratios, enhancing water bioremediation, and increasing shrimp survival. They are eco-friendly, biodegradable alternatives to antibiotics, regulating harmful gases, increasing dissolved oxygen, and playing a key role in disease prevention and water quality management in modern aquaculture systems.

Use of copepods and microbial populations in the aquamimicry system

Aquamimicry shrimp farming utilizes **copepods** as a primary live feed for stocked shrimp due to their superior nutritional quality compared to other live feeds like rotifers and brine shrimp. Copepods rapidly dominate the zooplankton community within two weeks, serving as an energy source and nutrient recycler in the marine food chain. Their rich biochemical composition includes essential fatty acids (EPA, DHA, ARA), carotenoids, amino acids, peptides such as taurine, minerals (selenium, iodine, copper, manganese), and vitamins, which are crucial for the survival, growth, and development of shrimp across all life stages. Their appropriate size makes them suitable for larval feeding, enhancing shrimp growth, immunity, and feed conversion efficiency. Besides copepods, the aquamimicry system supports diverse **microbial populations** such as phytoplankton, flagellates, cyanobacteria, and beneficial bacteria, influenced by environmental factors like temperature, light, salinity, and nutrient availability. Fermented carbon sources and probiotics help maintain the balance between zooplankton and phytoplankton, creating an optimal habitat while controlling harmful microbial blooms, including cyanobacterial toxins that can cause shrimp mortality. Microbial diversity, including dominant groups such as Proteobacteria, Bacteroides, and Bacillus, plays a critical role in shrimp gut health and disease resistance, helping reduce infections from pathogens like *Vibrio sp.*, Aeromonas, and viral diseases such as WSSV and VHS. The system's microbial community reflects the health of both shrimp and environment, with probiotic bacteria aiding water bioremediation, pathogen control, and overall productivity, making aquamimicry a sustainable and profitable shrimp farming approach.

Advantages

- Copefloc helps maintain stable water quality, converting ammonia into microbial biomass and reducing harmful substances.
- It minimizes water quality fluctuations and the formation of black soil at the pond bottom.
- Copefloc provides a natural food source (copepods), reducing reliance on commercial feeds and production costs.
- This leads to enhanced growth and survival rates in farmed species due to better nutrition and a healthier environment.
- The system improves biosecurity and reduces disease outbreaks by limiting water exchange and boosting immunity.

- It's considered environmentally sustainable, minimizing waste and the use of harmful chemicals and antibiotics.
- Copefloc systems are simpler to operate, avoiding the complexities and high costs of biofilters.
- They also improve the quality of aquaculture products by eliminating the use of chemicals and antibiotics.

Disadvantages

- Limited access to the necessary advanced technology, infrastructure, and expertise hinders widespread adoption.
- Improper management of the copefloc system can increase the risk of disease outbreaks and the emergence of new pathogens.
- Copefloc systems often require large treatment ponds, which may not be feasible for all culture methods.
- The integration of copefloc and biofloc systems, while potentially beneficial, presents challenges in design and management.
- Careful management of fermented carbon sources is needed to avoid inhibiting beneficial organisms or causing imbalances.
- There's a potential for disease outbreaks if producers fail to manage suspended solids in the water effectively.
- Research on the precise dynamics of copefloc microbial communities is still limited, making management more challenging.
- Copefloc systems might have higher energy requirements due to the need for continuous mixing and aeration.

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HARNESSING THE SUN: SOLAR DRYERS AND SMART TECHNOLOGIES FOR HIGH-VALUE CROPS IN NORTHEAST INDIA

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Abstract

Post-harvest losses of fruits and vegetables in India remain high, particularly in the humid and rain-prone Northeastern Himalayan region. Solar dryers provide a clean, efficient, and affordable solution by ensuring faster, safer drying of high-value crops such as large cardamom, Lakadong turmeric, Bhut Jolokia chilli, and kiwi. When integrated with decision support systems, machine learning, and simulation models, solar drying becomes more predictable and quality-driven. These smart technologies help farmers optimize drying time, preserve nutritional and sensory qualities, and access premium markets. This article explores the potential of solar dryer innovations to strengthen sustainable livelihoods in Northeast India.

Keywords: Solar Dryer, Post-Harvest Losses, Northeast India Crops, Machine Learning in Agriculture, Decision Support Systems

Introduction

The Northeastern Himalayan region of India is home to unique, high-value crops such as large cardamom, Lakadong turmeric, Bhut Jolokia chilli, and kiwi. Despite their market potential, farmers often face heavy post-harvest losses due to humid weather, irregular sunshine, and limited cold-chain facilities. Traditional drying methods, like open sun or smoke-based kilns, often reduce product quality and market value. Solar dryers provide a sustainable alternative by offering faster, cleaner, and safer drying. When combined with smart tools like decision support systems, machine learning, and simulation models, solar dryers can transform drying into a predictable, high-quality, and profitable process.

Drying is one of the oldest ways to preserve food. By removing moisture, it prevents the growth of fungi and bacteria, extending the shelf life of perishable products. In India's Eastern Himalayan states of the Northeast, where heavy rainfall, high humidity, and weak transport links often affect farmers, drying plays an even more critical role. It protects harvests, reduces losses, and allows farmers to add value to their produce. Studies across India show that post-harvest losses can be high: for fruits, losses range between 6.7–15.9%, while vegetables lose 4.6–12.4% before reaching consumers. Even a small reduction in these figures could mean significant income gains for farming households.

A solar dryer offers a simple but effective alternative to the common practice of drying produce in the open sun. At its core, a solar dryer is a covered chamber that traps the sun's heat and allows warm air to move over trays of produce. Unlike mats or tarps spread in the open, solar dryers keep products safe from dust, insects, and unexpected rain. They also maintain steady temperatures, typically between 40–60°C, which speeds up the drying process and gives the final product a brighter color and cleaner appearance. In recent experiments, passive solar dryers achieved remarkable results: 94% moisture removal in tomatoes and 84% in bottle gourd, far outperforming open-air drying.

For the Himalayan Northeast, solar dryers hold special promise because of the region's unique crops. Large cardamom, grown in Arunachal Pradesh and Sikkim, is traditionally cured in wood-fired *bhattis*. This method often darkens the capsules and adds smoke taint, lowering market prices. Studies show that the best curing temperature for cardamom is 45–55°C, a range that solar dryers can achieve more gently. In Meghalaya, Lakadong turmeric, celebrated for its high curcumin content, benefits from controlled drying that preserves its vibrant color and valuable compounds. Similarly, the fiery Bhut Jolokia (ghost chilli) of Assam and Nagaland retains its red hue and pungency when dried under controlled heat rather than left to dry slowly on humid days. And in Arunachal Pradesh, where kiwi production is rising, solar drying offers a way to turn fragile fresh fruit into durable slices and fruit leather, reducing dependence on cold chains.

While solar dryers already make sense, adding a layer of "smart" technology makes them even more powerful. A Decision Support System (DSS) is essentially a guidebook in your phone. Linked to simple sensors that record temperature and humidity, the DSS can suggest the best time to load the dryer, how thin to slice the produce, and when to stop drying. It can also log results for later use, ensuring consistency across batches. By combining local weather forecasts with real-time conditions, such systems help farmers avoid guesswork.

This is where machine learning (ML) steps in. By analyzing past drying batches, ML can learn how long it takes to dry a specific crop under certain conditions. It can then predict drying time based on today's sunshine or even warn of mold risk if the process is too slow in high humidity. For sensitive crops like cardamom, ML can connect the drying profile to expected aroma and color, helping operators stay within the quality-preserving range of 45–55°C. Even a simple phone camera can be paired with ML tools to assess the color of turmeric or chilli and provide quick feedback on whether the product is ready for market.

Another useful tool is the use of simulation models. Food scientists worldwide have developed mathematical models that describe how moisture leaves a product over time. These models, such as the Page or Henderson–Pabis equations, can be embedded into a phone app. For farmers, this means that with a weather forecast and a few inputs like slice thickness and tray load the app can display a curve showing how long drying will take that day. It can also suggest whether it is better to start drying in late morning after the fog has cleared, or whether a backup heating source might be needed.

Imagine a turmeric grower in Meghalaya starting the day with an app that checks the local weather and advises: "Start drying at 10:30 am, slice pieces 3–4 mm thick, expected drying time six hours." As the day progresses, sensors track chamber conditions and the app sends simple alerts, such as "stir trays now" or "extend drying by one hour." At the end of the day, the system confirms that the target moisture has been reached and generates a batch report with time, color photos, and expected grade. For buyers, such traceability builds trust; for farmers, it builds confidence in consistent quality.

The numbers support this vision. Controlled solar dryers not only shorten drying times but also produce brighter colors and higher grades compared with open sun. By replacing smoky *bhatti* curing, large cardamom fetches better market value. For turmeric, clean and uniform drying enhances curcumin content. For chilli and kiwi, consistent drying lowers spoilage and opens new processed-product markets. Techno-economic studies across India confirm that solar dryers can be profitable, especially when used for high-value crops in cold or humid regions.

In practical terms, a shared dryer in a village cluster might include a polycarbonate-covered chamber with trays, a black absorber surface, and a small solar-powered fan to move air on humid days. A few sensors for temperature and humidity, plus a phone to run the DSS app, complete the setup. By organizing this system through cooperatives or farmer-producer groups, the investment can be shared, and products can be branded and sold with confidence.

Of course, challenges remain. In the Himalayan climate, fog and rain can delay drying, so careful scheduling is key. Overheating must be avoided for spices and herbs, which lose their essential oils at high temperatures. Hygiene and safe storage are also critical, requiring clean trays, proper blanching when necessary, and airtight packaging. Finally, a small backup heater biomass or electric can ensure batch completion during cloudy spells.

The bottom line is clear. Solar dryers, when combined with decision support systems, machine learning, and simple simulation models, transform traditional drying into a predictable and profitable process. They not only reduce waste and improve quality but also connect Himalayan farmers to premium markets. With even one shared dryer, a community can create branded products bright red chillies, golden turmeric, fragrant cardamom, and tangy kiwi snacks that carry the proud label: "Solar-dried in the Himalaya."

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CHANGING GENDER ROLES: ARE INDIAN FAMILIES EVOLVING?

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Abstract

Gender roles in Indian families have long been defined by patriarchal values, where men and women were assigned distinct and often unequal responsibilities. Traditionally, men were seen as providers and decision-makers, while women were expected to manage the home and care for the family. However, shifts brought by urbanization, improved access to education, globalization, and the growing involvement of women in the workforce are beginning to challenge and transform these long-standing roles. This article examines how these social and economic changes are reshaping family dynamics in India. It explores both the progress made toward gender equality and the underlying resistance that maintains traditional expectations. By analyzing current trends and ongoing tensions, the article seeks to determine whether Indian families are truly moving toward a more egalitarian model or if older patterns of inequality are being restructured under a modern guise. The discussion provides a nuanced perspective on evolving gender roles within contemporary Indian households.

Introduction

Indian families have historically operated within rigid gender frameworks, where men held roles of economic providers and decision-makers, while women were confined to domestic responsibilities and caregiving. These divisions were deeply entrenched in cultural traditions, religious beliefs, and socio-economic systems, limiting women's autonomy and restricting their visibility in public spheres. Over time, however, various forces have begun to challenge and reshape these traditional roles. Expanded educational opportunities for women, economic liberalisation, digital connectivity, and the influence of feminist thought have collectively contributed to a re-examination of gender dynamics within households. Despite these shifts, the progress toward genuine gender equality within Indian families remains inconsistent and often superficial. Disparities based on geographic location, class, caste, and age continue to influence how gender roles are understood and enacted. In urban and more affluent settings, there is a visible move toward shared responsibilities and increased female participation in decision-making. However, in many rural or conservative households, traditional expectations persist, sometimes subtly repackaged in more modern language. The article delves into these complexities, questioning whether the observed changes reflect a fundamental transformation or merely cosmetic adjustments to patriarchal norms. For instance, while more women may be entering the workforce, they often continue to shoulder the majority of household duties, reinforcing the dual burden rather than dismantling gender hierarchies. Similarly, young men might support gender equality in principle but hesitate to challenge entrenched roles at home. By analysing these emerging patterns alongside persistent inequalities, this article offers a critical perspective on the state of gender roles within contemporary Indian families. It highlights the need for both structural and cultural change, suggesting that true gender equity will only be realised when deep-seated beliefs and social systems evolve alongside visible behavioural shifts.

Historical Context of Gender Roles in Indian Families

Historically, traditional Indian families—especially those rooted in Hindu joint family structures—functioned within a patriarchal framework. Men dominated decision-making and controlled property and inheritance, while women were relegated to domestic roles, often at the cost of their education and career aspirations. Social customs like arranged marriages, dowry practices, and a preference for male offspring further entrenched gender inequality. Although the 19th and 20th centuries witnessed early reform movements—including the outlawing of practices like sati, the promotion of women's education, and legal advancements granting women rights to inheritance—progress was gradual and frequently opposed by conservative societal forces. Despite these legal and educational reforms, the societal mindset remained largely unchanged for decades, keeping women's participation limited to household duties and reinforcing their subordinate status. Public and private spheres remained distinctly divided by gender, with women having minimal autonomy outside the home. These deep-rooted traditions laid the groundwork for the persistent gender norms seen in many families today.

Catalysts for Change

Several interrelated factors have accelerated the shift in gender roles within Indian families:

1. **Education and Employment:** Increased female literacy and higher education enrollment have opened doors to professional opportunities. According to the National Sample Survey (2019), the number of working women in urban areas has steadily risen, particularly in sectors like education, healthcare, and IT.
2. **Economic Liberalization:** Since the 1990s, India's economic liberalization has created a need for dual-income households, especially in urban centers. Women's financial contribution has led to greater bargaining power and increased visibility in decision-making.
3. **Media and Global Influence:** Exposure to global media, social platforms, and feminist discourse has challenged traditional gender stereotypes and created new aspirations, especially among younger generations.
4. **Legal and Policy Reforms:** Laws promoting gender equality—such as the Hindu Succession (Amendment) Act, 2005, and the Protection of Women from Domestic Violence Act, 2005—have provided legal backing to women seeking empowerment within families.
5. **Men's Changing Roles:** There is a growing, albeit slow, trend of men participating more in household chores and parenting, particularly among educated urban youth. The pandemic further accelerated this shift by blurring work-home boundaries.

Signs of Evolving Gender Roles

The evolution of gender roles is reflected in multiple areas of family life:

- **Parenting Styles:** Younger couples are increasingly adopting shared parenting models, with fathers taking active roles in childcare, attending school meetings, or preparing meals.
- **Household Chores:** While women still perform the majority of domestic labor, there is growing recognition—socially and within media—that household responsibilities should be shared.
- **Decision-Making:** In many middle-class and urban households, women now participate in key decisions such as children's education, financial planning, and property investments.
- **Marriage and Partnership:** There is a slow but noticeable move from arranged marriages to self-choice or hybrid models, giving women more say in partner selection and relationship dynamics.

- **Perception of Masculinity:** Traditional notions of masculinity—based on control, silence, and financial dominance—are being challenged by new models that value emotional openness and partnership.

Persistent Challenges

Despite visible progress, several barriers continue to hinder the full evolution of gender roles:

1. **Unequal Domestic Burden:** Even among working women, the burden of household chores and caregiving remains disproportionately high. The "double shift" phenomenon continues to impact women's mental and physical health.
2. **Workplace Discrimination:** Glass ceilings, wage gaps, and lack of maternity benefits or flexible work policies often push women out of the workforce after marriage or childbirth.
3. **Cultural Expectations:** Deep-rooted norms regarding obedience, sacrifice, and female modesty persist, especially in rural areas and traditional families.
4. **Violence and Control:** Domestic violence, marital rape, and moral policing still plague many women, limiting their freedom within and outside the household.
5. **Resistance from Older Generations:** Intergenerational conflicts often emerge when younger women assert independence, as older family members may see it as a threat to traditional values.

The Role of Men in Shaping New Gender Norms

Men play a vital role in challenging and transforming patriarchal systems. Promoting positive masculinity—where men actively engage in caregiving, show emotional openness, and uphold respect for women's independence—is essential for fostering gender equality. While global initiatives like MenEngage and HeForShe have made notable progress in shifting societal perceptions, there remains a need for more grassroots, culturally appropriate interventions to create a lasting impact. Male allies, especially within families and communities, can influence change by embodying egalitarian values in their daily lives. Fathers who demonstrate respect and partnership in their relationships offer powerful role models for both sons and daughters, helping to break cycles of gender bias. Similarly, schools, peer networks, and workplaces must reinforce inclusive behaviours by creating environments where equality is not only taught but practised. Encouraging men to be part of the conversation and solution is a crucial step toward achieving a more balanced and just society.

Policy Recommendations and Future Directions

To accelerate meaningful change, a multi-pronged strategy is necessary:

- **Education Reform:** Integrate gender sensitization into school curricula to challenge stereotypes early.
- **Parental Leave:** Implement equitable parental leave policies to encourage shared caregiving.
- **Media Responsibility:** Encourage realistic portrayals of gender roles in media and advertising.
- **Support Systems:** Provide community-based support for working women, including affordable childcare, safety measures, and mental health resources.
- **Legal Enforcement:** Ensure the implementation of existing gender-equality laws and establish mechanisms for grievance redressal within families.

Conclusion

Indian families are undoubtedly undergoing a period of significant transformation, yet the path toward genuine gender equality remains uneven and layered with complexities. While certain sections of society—particularly among the urban, educated middle class—are demonstrating progressive changes, deeply entrenched traditional norms continue to shape family dynamics in large parts of the country. Changes such as increased female participation in education and the workforce, or men taking on more domestic responsibilities, are encouraging. However, these shifts often coexist with persistent gender biases, signalling that transformation is still superficial in many contexts. Achieving true evolution in gender roles goes beyond simply reversing responsibilities or increasing women's visibility in public spheres. It requires a deeper, more fundamental dismantling of the ideologies that uphold patriarchal systems and assign fixed roles based on gender. These beliefs, often internalised and normalised across generations, must be challenged through both dialogue and daily practice. A meaningful shift must be both structural and emotional. Structural change involves policies, laws, and institutional support that promote equality and protect rights, while emotional change demands a reorientation of how family members view and treat each other. Respect, empathy, shared accountability, and open communication must form the foundation of these evolving relationships. Rather than replicating past inequalities in new forms, Indian families must strive for models that are flexible, inclusive, and emotionally intelligent. This includes redefining success, caregiving, leadership, and emotional expression in ways that are not limited by gender. It is through this holistic approach—where mutual empowerment and balance become the norm—that families can truly reflect the changing realities of contemporary life. Only then can the transformation from rigid patriarchal systems to equitable and compassionate family structures be fully realized.

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TEEN ANXIETY AND THE MYTH OF THE PERFECT LIFE

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Abstract

Adolescent anxiety has seen a significant increase in recent years, largely influenced by the unrealistic expectations set by social media and broader societal pressures. Today's teens are constantly exposed to idealized portrayals of success, beauty, and happiness, leading to feelings of inadequacy and self-doubt. This article examines the psychological impact of the so-called "perfect life" myth on adolescent mental health. It highlights how these distorted standards affect self-perception and contribute to anxiety. The discussion also emphasizes the critical need for emotional awareness, supportive relationships, and healthier digital habits to foster resilience and promote mental well-being among teenagers.

Introduction

Adolescence is a vital stage marked by the development of identity, emotional growth, and the need for social connection. Yet, today's teenagers navigate a contradictory reality: they are more digitally connected than ever, yet often feel emotionally isolated. Central to this paradox is the powerful and widespread "perfect life" narrative. Fueled by constant exposure to social media, intense academic pressure, consumer culture, and unattainable societal ideals, this myth fosters a distorted view of success and happiness. As teens strive to meet these unrealistic standards, many experience heightened stress, self-doubt, and anxiety. The overwhelming desire to appear flawless—academically, socially, and physically—can erode authentic self-esteem and emotional resilience. Recognizing the underlying factors behind this phenomenon is crucial for parents, educators, and mental health professionals. Only by addressing these pressures and fostering emotionally supportive environments can we help adolescents thrive in a world that often demands perfection over well-being.

Understanding Teen Anxiety in the Digital Era

Anxiety is not uncommon in adolescence, but its prevalence has intensified in recent years. According to the World Health Organization (2023), nearly 1 in 7 adolescents aged 10–19 experiences a mental disorder, with anxiety disorders being among the most common. These include general anxiety, social anxiety, and performance-related stress.

Digital technologies, while connecting teens globally, have also intensified performance pressure. Teenagers are not just comparing themselves to classmates or peers but to a constant feed of curated, filtered lives. Every scroll on Instagram or Snapchat offers images of seemingly perfect bodies, relationships, achievements, vacations, or lifestyles. The subtle message is clear: *you are not enough unless you have this*. This leads to internalized inadequacy and a distorted sense of self-worth.

The Myth of Perfection

The illusion of a "perfect life" influences adolescents through multiple dimensions, placing immense pressure on them to conform to unrealistic standards. In the realm of academics, teenagers are often expected to maintain high grades, engage in numerous extracurricular activities, and build impressive resumes for future educational and career opportunities. This relentless pursuit frequently comes at the expense of their personal interests, rest, and emotional health.

Physical appearance is another significant area where teens, especially girls, face intense scrutiny. Media and social platforms promote idealized and digitally altered beauty norms, leading to a surge in body dissatisfaction, low self-esteem, and even eating disorders.

Social validation has also taken a digital turn, with popularity now measured in likes, shares, and followers. To gain social acceptance, teens may adopt performative behaviors, sacrificing their authenticity and self-worth in the process.

Furthermore, modern society glorifies constant productivity. Leisure is no longer truly restful; instead, teens feel the need to use every moment to learn new skills, monetize hobbies, or showcase achievements online. This expectation to always be "doing something worthwhile" denies them the freedom to relax and just exist. Collectively, these pressures perpetuate a damaging cycle that fuels stress, anxiety, and emotional exhaustion among youth.

Such expectations create a psychological double bind: teenagers are asked to be both perfect and authentic, productive and relaxed, successful and balanced—an impossible feat that feeds chronic stress and self-doubt.

Psychosocial Implications

The gap between perceived societal ideals and actual lived experiences often leads adolescents to develop what psychologists describe as "imposter syndrome" and "perfectionist anxiety." Many teenagers begin to feel that others are handling life more successfully, which fosters insecurity and self-doubt. Factors like fear of missing out (FOMO), excessive comparison with peers, and constant monitoring of their own behavior further weaken their self-confidence. Adding to this challenge is the issue of emotional illiteracy—many teens lack the language, confidence, or safe spaces to express their negative emotions. As a result, their internal distress often goes unspoken and may appear in other ways, such as irritability, social withdrawal, declining academic performance, or physical symptoms like fatigue and headaches. If these emotional struggles remain unrecognized or unsupported, they can worsen over time and lead to more serious mental health problems, including depression, panic attacks, or substance use. Early emotional support is therefore crucial.

The Role of Families and Schools

Families may unintentionally contribute to the pressure of living an idealized life by focusing heavily on outward achievements rather than nurturing emotional health. Practices such as over-involvement, setting unrealistic expectations, or constantly comparing children to their peers can undermine a child's sense of self-worth and authenticity. Similarly, educational institutions often prioritize academic performance, standardized testing, and all-round excellence, placing students under immense pressure to constantly excel. This narrow focus can suppress emotional needs and discourage vulnerability or failure. Instead, schools should aim to create environments that value emotional honesty, allow space for rest, and recognize the importance of learning through setbacks. Emotional well-being must be seen as an essential part of education, not something secondary. Implementing Social and Emotional Learning (SEL) programs into the curriculum has shown to significantly reduce anxiety levels and strengthen students' coping skills, fostering resilience and healthier emotional development among adolescents in a pressure-filled world.

Strategies for Resilience and Authenticity

1. **Digital Literacy**: Teach teens to critically assess online content. Understanding that most online content is curated and edited can help reduce the urge for unhealthy comparison.
2. **Emotional Vocabulary**: Encouraging the use of "feeling words" and reflective journaling helps teens name and process their emotions more effectively.
3. **Mindfulness and Mental Health Practices**: Introducing practices like deep breathing, mindfulness, and cognitive restructuring helps regulate emotional responses to stress.
4. **Normalize Struggle**: Stories and role models that emphasize effort, failure, and growth over perfection must be highlighted in families, classrooms, and media.
5. **Parental Modeling**: Parents who are open about their own imperfections and emotional challenges model authenticity for their children.

Conclusion

The illusion of a "perfect life" presents an unrealistic and damaging standard that many adolescents struggle to meet. Far from being motivational, this myth imposes unattainable ideals that amplify feelings of inadequacy and stress, especially during a life stage already marked by significant emotional and psychological development. Teenagers, in their efforts to shape their identities and understand their self-worth, often find themselves overwhelmed by the pressure to conform to these false narratives. Whether it is flawless academic performance, idealized physical appearance, or curated lifestyles on social media, the constant comparison leads to growing anxiety and diminished self-esteem. Addressing this issue requires a united effort across all influential domains in a teenager's life. Families must shift their focus from outcomes and appearances to emotional well-being, fostering environments where vulnerability and imperfection are accepted. Schools, likewise, need to reconsider their definition of success—moving beyond marks and medals to embrace social-emotional development as an integral part of education. Digital platforms also bear responsibility by promoting more realistic content and actively discouraging toxic beauty and success standards. Equipping adolescents to resist the myth of perfection involves nurturing authenticity, building emotional resilience, and cultivating self-compassion. Encouraging open, honest discussions around mental health can help normalize struggles and reduce stigma. By fostering environments where young people feel safe to express their fears and flaws without judgment, we empower them to manage stress, embrace their uniqueness, and approach life with confidence. Ultimately, breaking free from the perfection narrative is not about lowering standards but redefining them—valuing emotional health, personal growth, and genuine connection over superficial ideals. This cultural shift is essential for supporting the mental well-being of today's youth and ensuring they grow into emotionally balanced and resilient adults.

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IMPACTS OF SEABED MINING ON MARINE FISHERIES: ECOLOGICAL RISKS AND SUSTAINABILITY CHALLENGES

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Introduction

Seabed mining, the extraction of minerals from the ocean floor, is emerging as a significant environmental concern, especially in relation to its impacts on marine fisheries and ecosystem sustainability (Gollner *et al.*, 2025). As demand grows for key minerals needed in industries such as renewable energy and electronics, deep-sea environments once largely untouched are now targeted by mining companies. However, the ecological risks and sustainability challenges associated with seabed mining remain profound and inadequately understood (Miller *et al.*, 2021). A major risk posed by seabed mining is the destruction of critical habitats that support diverse marine life, including commercially valuable fish species. Operations can result in permanent loss of biodiversity, disrupt spawning grounds, and jeopardize the recovery of deep-sea ecosystems, which may take decades or even centuries to rehabilitate, if at all. Mining activities generate sediment plumes, introduce heavy metals and toxins into the water column, and cause noise and light pollution all of which directly and indirectly threaten fish populations, marine mammals, and the functionality of marine food webs. Migratory species such as tuna are particularly vulnerable, as contamination and habitat disruption in one area can have cascading effects across broad oceanic regions (Alam *et al.*, 2025). The sustainability challenges extend beyond ecological impacts to include threats to food security and livelihoods for coastal communities reliant on fisheries. Small island nations and regions with economies tied to fishing face significant vulnerability as reductions in fish stocks jeopardize income, employment, and food supply (Szabó, 2025). Critically, the regulatory framework for seabed mining is still underdeveloped, and fishing industries have not been adequately included as stakeholders in decision-making processes. In sum, seabed mining poses substantial ecological risks and sustainability challenges that must be comprehensively addressed to protect marine biodiversity and the future of global fisheries.

Mechanisms of Seabed Mining

Seabed mining generally involves extracting minerals from polymetallic nodules, hydrothermal vents, and cobalt-rich crusts (Gollner *et al.*, 2025). The process includes (Fig. 1):

Sediment removal and dredging : causing physical habitat destruction.

Sediment plumes : dispersing fine particles into surrounding waters, smothering benthic and pelagic organisms.

Noise and light pollution : disrupting fish communication, spawning, and migration.

Release of toxic substances : potentially contaminating water and food chains.

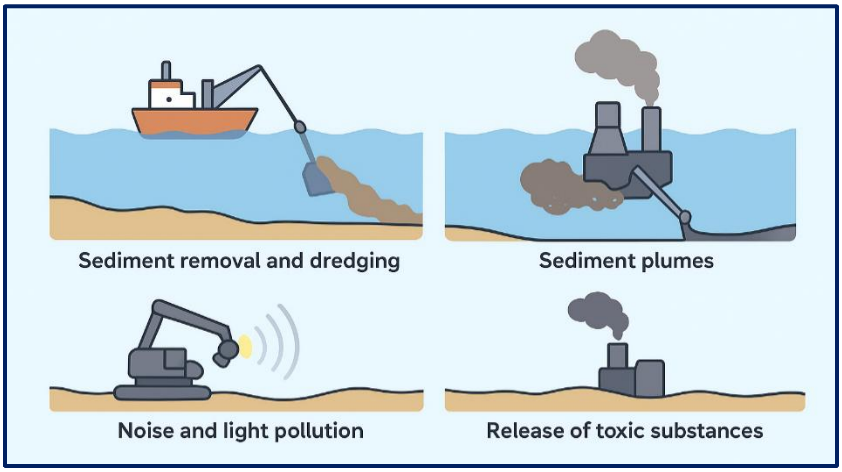

Fig. 1 Illustrate the mechanisms of seabed mining

Ecological Impacts of Seabed Mining on Fisheries

Seabed mining causes extensive environmental impacts by destroying deep-sea habitats, generating sediment plumes, releasing noise, vibration, and potential toxins, all of which disrupt fragile benthic ecosystems that recover extremely slowly (Gollner *et al.*, 2025). These disturbances not only reduce biodiversity and alter ecological processes but also pose significant risks to global fisheries by damaging habitats that support fish populations, contaminating the marine environment, and undermining ecosystem productivity. As a result, fish stocks may decline, threatening food security and livelihoods, particularly in coastal communities and small island nations dependent on fishing, while the broader global consequences of seabed mining on fisheries remain insufficiently explored. An overview of the environmental impacts of seabed mining is presented in Figure 2. Some major ecological impacts of seabed mining on fisheries are given below:

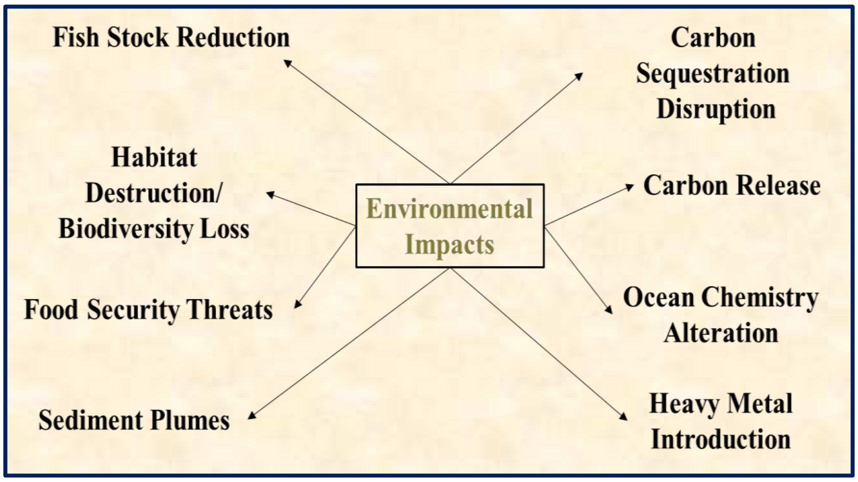

Fig. 2 Seabed mining impacts on marine ecosystems and fisheries

Habitat Destruction: Mining activities physically remove or alter deep-sea habitats that are crucial for fish spawning, nursery areas, and feeding grounds (Biju Kumar, 2025). The loss of seafloor ecosystems reduces available habitat for commercial and non-commercial species, directly impacting fish populations and their ability to recover or thrive.

Disruption of Spawning and Migration: Fish that depend on quiet, undisturbed environments for breeding may be displaced.

Biodiversity Loss: The deep-sea harbours unique species, many of which are poorly studied. Seabed mining can cause local extinctions, diminish genetic diversity, and disrupt ecological balances that are vital for sustainable fish stocks.

Sediment Plumes: Mining generates extensive sediment plumes that may drift for kilometres, smothering fish eggs, larvae, and benthic feeding areas (Harvey *et a*l., 2024). These plumes degrade water quality and can introduce heavy metals that bioaccumulate in the food web, affecting both fish health and seafood safety.

Food Web Disruption: By removing key habitats and impacting species, mining alters marine food webs. Such destabilization reduces prey availability, lowers ecosystem productivity, and shifts species composition negatively influencing fisheries yield.

Recovery Challenges: Deep-sea ecosystems and fish stocks recover extremely slowly, if at all. Many organisms have slow reproductive rates and specialized adaptations, meaning once habitats are destroyed, recovery may take centuries or may never occur. This results in long-term or permanent reductions in fisheries.

Socio-Economic Effects: Declines in fish catches caused by habitat loss, contamination, and reduced productivity threaten the food security and livelihoods of fishing communities, particularly in small island nations and coastal regions that rely heavily on marine resources.

Biodiversity Concerns

Seabed mining poses significant threats to marine biodiversity, particularly in fragile deep-sea ecosystems. These regions host a wide range of unique and poorly understood organisms, many of which are highly vulnerable to disturbance.

Loss of endemic and deep-sea species: The removal of seabed substrates and creation of sediment plumes can destroy critical habitats, leading to the loss of species that are often endemic to specific locations. Unlike shallow-water species, deep-sea organisms typically exhibit slow growth, late maturity, and low reproductive rates, making population recovery extremely limited or even impossible once disturbed.

Impacts on genetic diversity and ecosystem resilience: Biodiversity is a key driver of ecosystem stability and resilience. Disruption of deep-sea habitats may reduce genetic diversity among species, weakening the ability of ecosystems to adapt to environmental change. Such reductions in resilience increase the likelihood of long-term ecosystem collapse and reduce the productivity of adjacent fisheries.

Synergistic effects with climate change and ocean acidification: The ecological risks of seabed mining are intensified by global stressors such as rising ocean temperatures, acidification, and deoxygenation. These combined pressures can amplify the vulnerability of marine species, exacerbate biodiversity loss, and compromise ecosystem services that are vital for fisheries, carbon regulation, and global food security.

Sustainable Alternatives

While seabed mining offers access to critical minerals, its ecological risks highlight the need for sustainable alternatives that can meet resource demands without undermining marine ecosystems and fisheries. Key approaches include:

Recycling and Circular Economy: Expanding recycling of electronic waste and reusing metals from discarded products can significantly reduce the need for new mineral extraction. A circular economy approach emphasizes designing products for longevity, repair, and material recovery (Mohamed *et al*., 2025).

Land-Based Resource Efficiency: Improving mining efficiency and reducing waste in existing terrestrial operations can limit the environmental footprint compared to starting large-scale seabed mining.

Material Substitution and Innovation: Developing alternative materials or technologies that rely less on rare earth elements and metals can decrease dependence on seabed resources. For instance, advances in battery technology are exploring reduced use of cobalt and nickel.

Marine Protected Areas (MPAs): Designating ecologically sensitive deep-sea regions as MPAs can safeguard biodiversity and fisheries while ensuring mining does not encroach on critical habitats (Roberts, 2024).

Strengthened Governance and Precautionary Principle: Applying stringent environmental standards, robust monitoring, and precautionary approaches at both national and international levels can delay or prevent harmful mining until scientific knowledge is sufficient.

Investment in Renewable Resource Industries: Shifting focus toward sustainable industries such as offshore renewable energy, eco-tourism, and sustainable fisheries can provide economic growth without depleting fragile deep-sea ecosystems.

Future Directions and Challenges

The future of seabed mining and its implications for fisheries will depend on how well science, policy, and industry align to balance resource needs with ecological protection. Research is urgently required to assess long-term impacts on fish stocks, food webs, and ecosystem productivity. While technological innovations may help reduce some environmental damage, without robust international regulations, the risks to fisheries and food security will remain considerable. The International Seabed Authority (ISA) plays a key role in shaping global mining governance, but current frameworks remain incomplete and precautionary measures are still contested. Inclusion of fisheries stakeholders, coastal nations, and small island states will be vital to ensure fair and sustainable outcomes. Looking ahead, sustainable strategies such as expanding recycling, developing material substitutes, and strengthening marine conservation could reduce the pressure for seabed mining while protecting fisheries and safeguarding ocean health for future generations.

Conclusion

Seabed mining carries substantial ecological risks that threaten marine ecosystems and fisheries. Future strategies should prioritize strict regulation, development of sustainable alternatives, and deeper research into ecological impacts. Strengthening investment in marine conservation and science is crucial to balance economic interests with long-term environmental sustainability.

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RECENT ADVANCES IN AQUACULTURE AND FISHERIES

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Abstract

Aquaculture stands at a technological crossroads, transforming to meet the growing needs of global food security and environmental stewardship. In recent years, the sector has rapidly adopted integrated water management, microbial technologies, precision monitoring, alternative feeds, and circular economic models. These advances have significantly improved efficiency, sustainability, and resilience. This article delves into the key innovations shaping modern aquaculture and their implications for the industry's future.

Introduction

Aquaculture has emerged as the fastest-growing food production sector, now supplying over half of all seafood globally. The intensifying pressure on wild fish stocks has necessitated the expansion of farmed aquatic foods. However, this rapid growth introduces challenges such as environmental impact, resource allocation, disease risks, and the need for sustainable management. Innovative solutions—including cutting-edge infrastructure, digital technologies, and new feed sources—are now being adopted to overcome these obstacles. The following sections provide a comprehensive overview of these transformative advancements, exploring how they address the ecological, social, and economic dimensions of aquaculture.

Technological Innovations in Aquaculture

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are revolutionizing the way fish and other aquatic species are farmed. RAS involves continually filtering and reusing water within a closed-loop system, dramatically minimizing water intake and wastewater discharge. Advanced mechanical and biological filtration processes remove waste products, creating stable conditions ideal for high-density aquaculture. By drastically reducing water consumption—up to 99% compared to conventional pond or cage culture—RAS enables sustainable production in water-scarce areas or urban environments. While initial investments can be high, the operational savings, reduced environmental impact, and ability to site farms near consumers make RAS an increasingly attractive option.

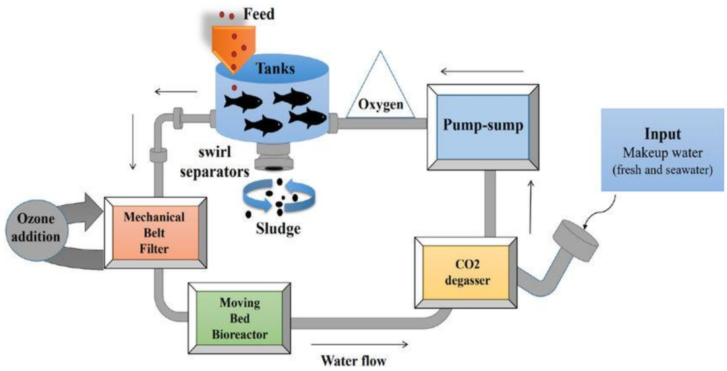

FIG1: RECIRCULATING AQUACULTURE SYSTEM (RAS)

Biofloc Technology (BFT)

Biofloc Technology (BFT) leverages the natural formation of microbial aggregates—called bioflocs—in aquaculture waters. These bioflocs assimilate excess nutrients, particularly nitrogen from fish waste, converting it into microbial protein that can be consumed by the farmed stock. This dual function significantly reduces nutrient-rich outflows and provides supplementary food, improving feed efficiency and lowering costs. BFT also allows for high-density cultivation with minimal water exchange, supporting production in regions where water is limited or effluent regulation is strict. Originally developed for shrimp and tilapia farming, BFT is now widely adopted across Asia and South America for its environmental and economic benefits.

FIG 2 : BIOFLOC TECHNOLOGY

Offshore and Open-Ocean Farming

Advances in offshore engineering have enabled the deployment of robust, self-sustaining aquaculture cages in the open ocean. By moving fish pens farther from shore, these systems reduce competition with coastal users and lessen impacts on sensitive nearshore ecosystems. Open-ocean farming sites benefit from cleaner water, stronger currents, and improved fish health, allowing for greater production capacity and sustainability. The technology also opens up vast new areas for aquaculture expansion, offering opportunities to meet the global demand for seafood with reduced environmental tradeoffs.

FIG 3 : Open ocean Farming

Digitalization and Precision Aquaculture

IoT, Sensors, and Automated Monitoring

The integration of Internet of Things (IoT) devices and smart sensors is transforming aquaculture management. These sensors continuously monitor water quality factors such as temperature, dissolved oxygen, pH, and ammonia, transmitting real-time data to cloud platforms. Automated alarms and analytics allow for early detection of suboptimal conditions or disease outbreaks, enabling rapid intervention. Automated monitoring also supports optimized feeding by adjusting schedules and feed amounts according to live conditions, reducing food waste and improving animal health. This real-time data-driven approach enhances biosecurity and operational efficiency, making aquaculture more reliable and scalable.

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning are reshaping aquaculture by making sense of the massive data streams generated on modern farms. AI-driven models forecast disease outbreaks, predict optimal feeding times, and automate tasks like grading and sorting. Computer vision tools—powered by underwater cameras—assess fish health, count stock, and monitor behavior with superior accuracy. This automation decreases labor needs, improves growth rates, and reduces costs. With AI, farms can dynamically adjust management strategies, maximizing productivity while minimizing risks and environmental footprints.

Precision Feeding Technologies

Precision feeding technologies automate the delivery of feed to cultured species, using computer-controlled systems to ensure each feeding aligns with the animals' growth stage and environmental conditions. These systems prevent over- or under-feeding, significantly lowering feed costs (typically the largest operating expense) and minimizing uneaten feed that could pollute farm waters. Precision feeding contributes directly to improved growth, better feed conversion ratios, and more sustainable operations, especially at commercial scales.

Sustainable Practices and the Circular Economy

Alternative Protein Feeds

A major challenge in aquaculture has been the reliance on fishmeal and fish oil harvested from wild fisheries, which is unsustainable at scale. Significant recent progress has been made in developing alternative feeds—using insect protein, microalgae, single-cell proteins, and plant-based ingredients. These novel feed sources offer a reduced environmental footprint, lower dependence on wild stocks, and competitive or superior nutritional profiles. Algae and insect-based feeds, in particular, recycle waste or utilize minimal land and water, aligning with broader goals of circular economy and resource valorization.

Integrated Multitrophic Aquaculture (IMTA)

Integrated Multitrophic Aquaculture (IMTA) mimics natural food webs by co-cultivating species from different trophic levels—such as fish, shellfish, and seaweed—in a single system. Waste nutrients produced by fed species (e.g., fish) are absorbed and utilized by extractive species (e.g., seaweeds and filter feeders), upgrading waste into valuable biomass. IMTA boosts resource utilization efficiency, minimizes pollution, and increases the overall yield and resilience of aquaculture ecosystems, supporting both environmental and economic goals.

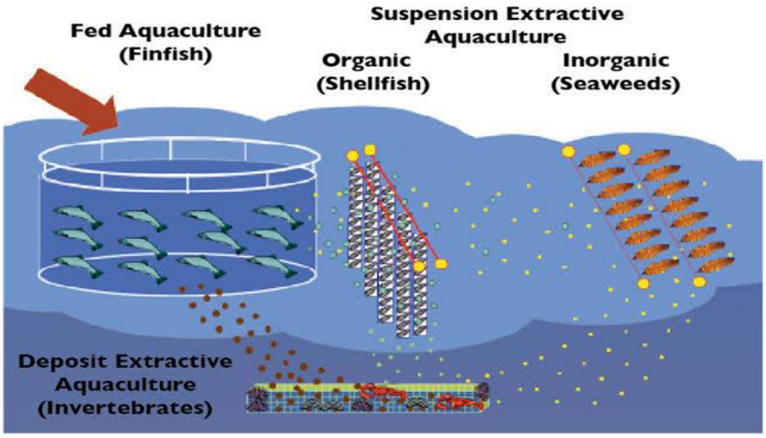

FIG 4: Integrated Multitrophic Aquaculture (IMTA)

Aquaponics

Aquaponics is an innovative approach that couples fish farming with hydroponic plant cultivation. In these closed systems, nutrient-rich water from aquaculture is used to nourish plants, which in turn help filter and clean the water for reuse by the fish. Aquaponics maximizes resource efficiency, uses 90% less water than traditional Aintegrated griculture, eliminates the need for artificial fertilizers, and enables food production in urban or marginal environments. This technology is gaining popularity for urban food security and sustainable local agriculture.

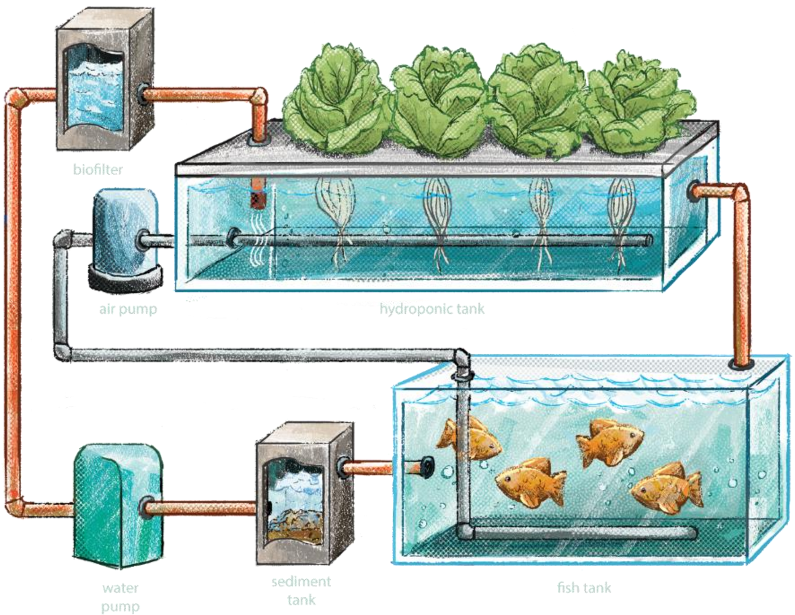

FIG 5 : AQUAPHONICS

Resource Valorization and Renewable Energy

Aquaculture operations are increasingly exploring ways to reuse by-products and integrate renewable energy. Fish waste and processing residues are processed into bioenergy, fertilizers, or ingredients for other industries, reducing pollution and supporting economic diversification. The adoption of solar and wind energy reduces reliance on fossil fuels, cutting greenhouse emissions and operating costs. These shifts contribute to a circular, sustainable aquaculture value chain.

Social and Economic Dimensions

Urban Aquaculture

Urban and vertical aquaculture systems are making it feasible to farm fish and seafood within city environments, utilizing abandoned buildings, rooftops, or purpose-built vertical farms. By producing seafood near consumers, these operations drastically reduce transport costs and emissions ("food miles"), improve product freshness, and generate jobs in local communities. Urban aquaculture addresses both environmental and social sustainability, enhancing urban food resilience.

Blockchain for Traceability

Blockchain technologies offer traceability solutions throughout the aquaculture supply chain, from hatchery to harvest and distribution. This secure, transparent tracking satisfies increasing consumer demands for proof of ethical sourcing, quality assurance, and food safety. Blockchain-enabled records deter fraud, ensure regulatory compliance, and provide accountability for responsible farm management, bolstering trust across global seafood markets.

Policies, Guidelines, and Partnerships

International organizations have guided aquaculture's growth through the establishment of sustainability guidelines, such as the FAO's Guidelines for Sustainable Aquaculture (GSA). These encompass the entire production and supply chain, emphasizing responsible resource use, community engagement, and transparent governance. Partnerships between governments, industry, and researchers foster innovation and ensure that economic advances also promote broad-based social and environmental benefits.

Conclusion

Aquaculture in 2024–2025 is at the forefront of a technological and ecological transformation. Advanced water systems, microbial technologies, digital management tools, novel feed sources, and circular economy principles are enhancing productivity and sustainability. As these innovations are accompanied by robust policy frameworks and transparency, aquaculture is positioned not just as a solution to global food needs—but as a model industry for sustainable, resilient, and inclusive growth. Continued investment and research will ensure that these gains are universal and enduring.

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THE HIDDEN WEB BENEATH THE SOIL: A JOURNEY INTO THE WORLD OF MYCORRHIZAL FUNGI

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Abstract

Mycorrhiza, first reported by frank (1885) is a mutualistic relationship between fungal hyphae and plant roots. In which there is a reciprocal exchange of nutrients. mycorrhiza enhances plant growth and development by special mechanisms and adaptations. This article explains mechanism, function, Importance, available formulations and limitations in mass multiplication of mycorrhiza.

Key words : Mycorrhiza, symbiotic association

Introduction

Imagine a world beneath your feet—an underground network where plants communicate, share nutrients, support each other during times of stress, and even warn their neighbours of danger. This hidden, intricate web is made possible by a fascinating group of organisms known as mycorrhizal fungi. Though invisible to the naked eye, they are among nature's most powerful allies in building healthy ecosystems and supporting sustainable agriculture.

Mycorrhiza refers to the symbiotic association between plant roots and certain types of fungi. The term itself comes from the Greek words *"mykes"* (fungus) and *"rhiza"* (root), literally meaning "fungus-root." In this relationship, both the plant and the fungus benefit, making it a classic example of mutualism. The plant, through its roots, offers carbohydrates—sugars produced during photosynthesis—as food for the fungus. In return, the fungus significantly boosts the plant's ability to absorb water and essential nutrients, especially phosphorus, from the soil.

This article delves into the mechanisms of this relationship, explores its functional roles, and highlights the potential of mycorrhiza in sustainable agriculture. It also discusses the challenges in mass production of mycorrhizal inoculants and their current limitations, along with emerging solutions and future directions.

How Do Mycorrhiza Work?

The functionality of mycorrhizal fungi lies in their unique ability to extend far beyond the plant's own root system. When fungal spores in the soil encounter a compatible plant root, they begin to colonize it. Specialized fungal structures known as hyphae—long, thread-like filaments—grow into the soil, increasing the root's surface area exponentially.

In the case of arbuscularmycorrhizal fungi (AMF), which are a type of endomycorrhiza, the fungal hyphae penetrate the plant root cells and form intricate tree-like structures called arbuscules. These are the sites of nutrient exchange between the fungus and the plant. Some fungi also develop vesicles, which are storage structures that help in long-term nutrient supply. These structures can be observed under the microscope using specific staining techniques, providing a vivid glimpse into this hidden world.

This symbiotic setup acts like a living extension of the plant's root system, allowing access to water and minerals that lie well beyond the reach of root hairs. The fungal hyphae can penetrate microscopic pores in the soil and extract phosphorus (P), zinc (Zn), copper (Cu), and other micronutrients with great efficiency.

Functional Role of Mycorrhizal Fungi in Ecosystems

The benefits of mycorrhiza extend far beyond nutrient acquisition. They play a multifaceted role in promoting plant health and improving soil quality.

- **Enhanced Nutrient Uptake**: Mycorrhizal fungi are particularly efficient in solubilizing and transporting phosphorus, which is often poorly mobile in soil. They also help in the uptake of zinc, copper, and sometimes nitrogen.
- **Improved Soil Structure**: The presence of fungal hyphae contributes to the formation of stable soil aggregates, which enhances aeration, water infiltration, and root penetration.
- **Stress Tolerance**: Mycorrhiza help plants withstand environmental stress, such as drought, salinity, and heavy metal toxicity, by improving water absorption and activating stress-response genes.
- **Disease Resistance**: Certain mycorrhizal associations can induce systemic resistance in plants, making them more resilient against root pathogens and soil-borne diseases.
- **Communication Network – The Common Mycorrhizal Network (CMN)**: Perhaps the most intriguing function is the ability of some mycorrhizal fungi to form a network linking multiple plants together. This "wood wide web", as it's sometimes called, allows plants to share resources—like water and nutrients—or even chemical signals, helping neighbours in need or warning them of impending threats like herbivore attacks.

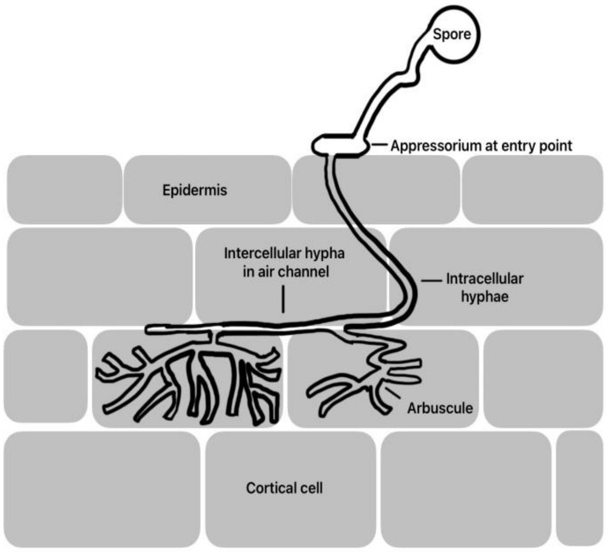
Types of Mycorrhiza: Are They All the Same?

Mycorrhizal associations are not one-size-fits-all. Broadly, they are classified into two major types:

1. **Ectomycorrhiza (ECM)**:
    - These fungi form a dense sheath (mantle) around the plant roots but do not penetrate the root cells.
    - They grow into the spaces between root cells, forming what is known as a Hartig net.
    - Ectomycorrhizal associations are commonly found in forest trees, especially conifers like pine, oak, birch, and beech.

- These fungi can form fruiting bodies like mushrooms and are visible to the naked eye.

2. **Endomycorrhiza (particularly ArbuscularMycorrhiza)**:
   - These penetrate the cortical cells of roots and form arbuscules and vesicles.
   - They are the most widespread form of mycorrhiza, especially dominant in tropical and agricultural soils.
   - Unlike ectomycorrhiza, they do not produce large fruiting bodies, and their presence can only be confirmed microscopically.



Development of Arbuscular Mycorrhiza

Some plants may form specialized forms of mycorrhiza like ericoid or orchid mycorrhiza, adapted to very specific environments and hosts.

Challenges and Limitations in Mycorrhizal Application

Despite their enormous ecological importance and potential benefits in agriculture, the practical application of mycorrhiza faces several hurdles:

- **Host Specificity**: Not all mycorrhizal fungi are compatible with all plant species. Some plants form very strong associations, while others are less responsive. Selecting the right combination is crucial.
- **Soil Conditions**: High levels of available phosphorus or chemical fertilizers can inhibit colonization by mycorrhiza, as plants tend to rely less on fungal assistance when nutrients are abundant.
- **Sensitivity to Chemicals**: Pesticides and fungicides, commonly used in conventional agriculture, can negatively affect mycorrhizal colonization and function.
- **Production Limitations**: Mass multiplication of mycorrhizal fungi is not as straightforward as bacterial biofertilizers. These fungi require a living host (usually plant roots) to complete their life cycle, making pure culture production costly and labor-intensive.
- **Variable Field Performance**: Even when applied as inoculants, the effectiveness varies across soil types, climates, and cropping systems. This unpredictability limits widespread adoption.

Applications in Agriculture: A Tool for Sustainability

With increasing pressure to reduce chemical inputs and enhance soil health, mycorrhizal fungi are emerging as a critical component of sustainable agriculture. Their benefits include:

- **Reducing Chemical Fertilizer Use**: By enhancing nutrient uptake, especially phosphorus, mycorrhiza can reduce dependency on synthetic fertilizers, saving costs and reducing environmental pollution.
- **Improving Transplant Survival**: In nurseries and greenhouses, pre-inoculating seedlings with mycorrhiza helps them establish better when transplanted into the field.
- **Enhancing Water Use Efficiency**: By increasing root access to water, mycorrhiza help plants withstand **drought stress**, an increasingly important trait in the face of climate change.
- **Boosting Disease Resistance**: Mycorrhizal colonization can prime plant immunity, offering an additional line of defense against soil-borne pathogens.
- **Rehabilitation of Degraded Lands**: In land reclamation projects and reforestation efforts, mycorrhizal inoculation can accelerate the establishment of native plant species.

Conclusion and Future Perspectives

Mycorrhizal fungi are nature's silent engineers, tirelessly working beneath the soil surface to maintain balance and productivity in ecosystems. Their role in nutrient cycling, soil stabilization, and plant health makes them indispensable for eco-friendly and resilient agriculture.

However, to fully unlock their potential, further research is needed to overcome production and field application challenges. Advances in biotechnology may soon enable cost-effective and large-scale production of species-specific inoculants. Additionally, developing customized formulations tailored to regional crops and soils will improve field-level success.

By integrating mycorrhizal technology into our agricultural systems, we not only reduce the environmental footprint of farming but also move one step closer to restoring the natural harmony between plants and the soil microbiome.

As we tread the path toward sustainable food production, it's time we listened to the quiet but powerful voice of mycorrhiza—the underground network sustaining life above.

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UNLOCKING THE POTENTIAL OF BANANA BLOSSOMS: NUTRITION, WELLNESS, AND UTILIZATION

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Abstract

Bananas are a low-cost staple in many developing countries, yet only the fruit is typically consumed while the banana blossom (or heart) is discarded. Rich in fiber and bioactive compounds such as alkaloids, tannins, flavonoids, and phenolics, the blossom offers anti-cancer, antimicrobial, and antioxidant benefits. Widely used as a food additive in parts of Asia, it remains underutilized. This review highlights its nutritional potential and advocates for its incorporation into value-added food products for enhanced health and functional benefits.

Introduction

Banana (Musa), a member of the Musaceae family, is the fourth-largest food crop in the world, after wheat, rice, and maize. It contributes a crucial role in the profit-making of many developing countries (Salvador, 2018). Currently, banana is grown on 5.64 Mha of land worldwide (Evans *et al.,* 2020). India is the world's largest banana producer, accounting for 27% of worldwide banana production (Kumar *et al*., 2013). Banana is cultivated primarily for its fruit, which produces several tons of waste and underused by-products (Essien *et al*., 2005; Shah *et al*., 2005; Yabaya and Ado, 2008; Padam *et al*., 2014).

Banana Blossom

One such by-product waste is banana blossom. The Blossom of the banana also considered the “Banana Heart” and “Banana flower”, can be eaten raw or cooked (Komal and Kaur, 2019). Historically, the banana blossom has tremendous health benefits and is often used as a food additive in several Asian nations, including, Indonesia, Thailand, and Sri Lanka. It is eaten raw and fresh, used as pickles, dehydrated vegetables, and canned foods. It is a popular meal in Sri Lanka, where it is served as curry or as a boiled or fried salad (Salvador, 2018). Simultaneously, the banana blossom is a rich source of minerals and antioxidants that have been used in traditional medicine to treat constipation, bronchitis, and ulcer disorders (Sheng *et al.,* 2010). The banana blossom is also a good source of high-quality protein, dietary fiber, vitamins, and minerals like magnesium, iron, and copper, all of which have anti-cancer properties (Tasnim, 2020). Banana blossom contains biologically active compounds such as antioxidant activity, total phenolic compounds, vitamins, and minerals that aid in the treatment of diabetes, weight loss, gastrointestinal health, and the relief of menstrual cramps (Divya *et al*., 2016; Thaweesang, 2019).

Nutritional Properties Of Banana Blossom

A. Dietary Fiber

Obesity has risen dramatically in recent decades. Obesity in Westernized countries ranks high among public health issues because it is associated with adverse health outcomes and high economic costs (Kuczmarski *et al*., 1994; Pi-Sunyer*et al*.,1993; Burton – Freeman, 2000). Dietary fiber (DF) is classified as soluble (SDF) or insoluble (IDF). IDF is mainly involved in mechanical peristalsis in the gastrointestinal tract, while SDF is involved in the availability of carbohydrate and lipid metabolism (Sema- Cock *et al.*, 2016). Blossoms of bananas are often considered a rich source of fiber, which has beneficial health and disease-prevention effects in medical nutrition therapy (Salvador, 2018). Many studies have been conducted on the banana blossom to evaluate its potential value as a source of dietary fiber.

B. Antioxidant

Antioxidants were introduced into the food industry during the 20th century as a means to limit the degradation of stored foods due to oxidation. The use of natural substances as antioxidant additives in food products has gained a lot of attention in recent years, resulting in the development of novel combinations of antioxidants and new food products (Admassu and Kebede, 2019). Antioxidants are compounds that can neutralize free radicals. Free radicals are unstable and reactive due to an unpaired electron in the outer orbit. Despite the fact that the human body has mechanisms to combat free radical-induced damage, such as "oxidative stress," accumulative oxidative damage leads to a wide range of disorders (Skrovankova*et al.*, 2015). The ready-to-eat product sector has grown rapidly in response to rising customer demand for quick foods. Meanwhile, to protect the quality of ready-to-eat foods, synthetic antioxidants (such as butylated hydroxyanisole and butylated hydroxytoluene) are increasingly used. Food makers are looking for natural alternatives to synthetic antioxidants as public concerns about synthetic antioxidants grow (Brewer, 2011). Banana blossoms, which are high in natural antioxidants, are extensively used as food additives in many Asian nations, including Indonesia, Sri Lanka, and Thailand, to combat this problem (Sheng *et al.*, 2010). According to banana blossoms are always discarded as agricultural waste, but they are also high in phytochemical constituents, antioxidant properties, and medicinal benefits, making them a potential functional food with a wide range of nutraceutical values that are important in maintaining good health (Suffi *et al.*, 2021).

C. Other Nutrients Banana

flowers are considered a natural food additive in many Asian countries due to their high nutritional content, which includes fiber, vitamins, protein, and minerals such as phosphorus, iron, zinc, and potassium. It is also an excellent source of flavonoids, tannins, saponins, etc (Soni and Saxena, 2021). Reported that the banana blossoms had protein content from 8.89 % to 10.35 % dry weight, fat content from 4.95 % to 15.69 % dry weight, and moisture content from 92.29 % to 93.73 % flesh weight, ash content from 9.88 % to 12.25 % dry weight (Florent *et al.*, 2015). Moreover, the banana flowers were reported to be high in micronutrients such as potassium (6480 mg/100g), calcium (687 mg/100g), magnesium (273 mg/100g), and phosphorus (211 mg/100g). Similarly, observed that the moisture, crude protein, fat, crude fiber, and total ash values of fresh banana blossoms were as follows: 88.75g/100g, 21.01 g/100g DM, 6.02g/100g DM, 20.31g/100g DM, and 8.74g/100g DM respectively. In addition, the banana flower had calcium of 3.42 mg/g DM and 0.13 mg/g DM of iron (Wickramarachchi and Ranamukhaarachchi,2005).

Health benefits of banana blossom

Banana blossom is regarded as an important functional food since it has various health benefits such as action against hyperglycemia, inflammation, and microbes . Since the flower is rich in medicinal properties, it is widely used to treat health problems related to the heart, menstrual cycle, and endocrine system. Blossom is reported to cure asthma, stomach and throat ulcers, itching of the eyes, and blood flow problems (Soni and Saxena, 2021; Singh *et al.*, 2016).

Utilization of banana blossom in value-added products

Banana blossoms, also known as banana hearts and banana flowers, are edible raw, or cooked and are a nutritional food source present in the banana plant's tip. Banana blossoms are also recognized for their medicinal properties (Komal and Kaur, 2019). Many Asian countries, including Malaysia Sri Lanka, the Philippines, and Indonesia. Consume the nutritious blossom as a vegetable. It is also eaten in curry and as a salad with rice and wheat bread (Wickramarachi and Ranamukhaarachchi, 2005). In recent years, agricultural by-products are receiving more attention for their potential value for human health through processing. Flowers are a by-product of postharvest cultivation and a good source of dietary fiber. Incorporated fiber-rich flower into a variety of foods and beverages, helps to generate value-added and functional foods that meet the demand for dietary fiber supplements (Begum and Deka, 2019).

Value-Added Products from Banana Blossom

A. Probiotic Drink

Rompies*et al*. (2021) developed three variations of probiotic fermented drinks using banana flower (Musa balbisiana), banana leaf, and CO_2-free water in ratios A (1:0.5:0.5), B (2:1:1), and C (3:2:2). Inoculated with *L. paracasei* under anaerobic conditions, vitamin C content and antioxidant activity were measured. Sample C showed the highest vitamin C (77.92 mg/100g) and antioxidant activity, attributed to the nutrient synergy of flowers and leaves. The drink offers fiber, bioactive compounds, prebiotics, and probiotics, supporting immunity and anti-inflammatory benefits.

B. Enriched Plain Cake

Tasnim *et al*. (2020) evaluated plain cakes fortified with pretreated banana blossom flour (honey-citric acid, citric acid solution, or rice rinsed water). Rice rinsed water–treated flour (RRW-BBF) improved protein, fat, ash, and moisture, while reducing carbohydrates and energy. Fortification up to 4% enhanced nutritional value without compromising sensory quality.

C. Biscuits

Elaveniya and Jayamuthunagai (2014) produced high-fiber biscuits using banana blossom powder pretreated with citric acid or rice rinsed water to inhibit enzymatic browning. The flour showed good functional properties and high phenolic content. Biscuits retained significant protein, fiber, and antioxidant activity, offering a nutrient-dense snack option.

D. Nut Chocolate

Komal and Kaur (2019) incorporated banana blossom into nut chocolate at 10%, 20%, and 30% levels. Sensory evaluation showed 20% inclusion yielded the highest overall acceptability compared to control and other variations.

E. Mushroom Balls

Chaiwongsa*et al*. (2021) formulated plant-based shiitake mushroom balls with banana blossom at ratios 100:0 to 25:75. The 50:50 blend scored highest in appearance and overall quality. Up to 20% banana blossom fortification improved health value without affecting sensory properties.

F. Ready-to-Cook Dehydrated Product

Wickramarachchi *et al*. (2005) developed a dehydrated banana blossom product resistant to enzymatic browning without sulfating agents. Blossoms sliced to 3 mm, treated with 0.2% citric acid, and dried at 50°C for 6 hours retained quality and sensory attributes. Packaging in aluminum foil–laminated polyethylene extended stability beyond one month.

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BEYOND HONEY: A GUIDE TO HANDLING ROYAL JELLY, BEE VENOM, AND PROPOLIS

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Abstract
Royal jelly is a milky white substance, also known as bee milk, produced by the worker caste to feed the queen and young larvae. Venom is a defensive substance produced by the worker caste to defend the colony from enemies. On the other hand, propolis is a gummy substance prepared by the worker caste to seal the comb. These byproducts have huge nutritional and medicinal importance to humans. In apiary management, apart from honey yielding, these byproducts also gave additional income for the farmers. This article explains the extraction and processing of royal jelly, bee venom, and propolis.

Keywords: royal jelly, bee venom, propolis

Introduction
Honey bees' byproducts include honey, beeswax, bee pollen, royal jelly, and bee venom.

Royal jelly is a white, milky, and creamy substance secreted by the hypopharyngeal glands of worker bees. Its composition includes 60-70% water, 9-18% proteins, 10-16% carbohydrates, and 3-6% lipids, along with various vitamins, minerals, and free fatty acids. All larvae are initially fed royal jelly for the first three days of life, but only queen larvae continue to receive it beyond that period.

Bee venom, also known as apitoxin, is a defensive secretion produced by worker bees through glands associated with their stinger. It contains several biologically active compounds, including melittin (40-60%), apamin, phospholipase A2, hyaluronidase, histamine, and Mast Cell Degranulating (MCD) peptide.

Propolis (bee glue) is a gummy, strongly adhesive, resinous substance prepared by bees through the collection of resins from cracks in tree bark and leaf buds. These resins are then masticated, mixed with salivary enzymes and beeswax, and finally used to seal holes in the honeycombs. Propolis consists of approximately 50% resin and balsam, 30% wax, 10% aromatic oils, 5% pollen, and 5% organic debris (El-Didamony *et al*., 2024).

Many beekeepers in India are mainly focusing on the extraction of one bee byproduct known as honey; indeed, apart from honey, other byproducts are more valuable if they are properly processed and sold in the market. The main reason is due to a lack of awareness about the importance of other bee byproducts and correct knowledge about the processing. This article explains the importance and procedure for extracting other bee byproducts such as royal jelly, bee venom, and propolis.

Royal Jelly products and processing
Royal jelly is often referred to as the "elixir of life" due to its significant role in the development and longevity of queen bees. The extended lifespan of queen bees is largely attributed to their exclusive

diet of royal jelly. This substance possesses various beneficial properties, including antioxidant activity, immune system support, anti-ageing effects, and the ability to extend the life span of organisms.Royal jelly has a pungent, phenolic odor, a sour taste, and a fluid, paste-like consistency, with a density of approximately 1.1 g/cm³. Due to its health-promoting qualities, it is widely used as a dietary supplement and as an ingredient in health foods, pharmaceuticals, and cosmetic products. On average, a single beehive can yield around 300 to 500 grams of royal jelly annually. Worker larvae consume royal jelly as it is produced, but queen larvae cannot consume it as quickly, so some amount accumulates in the cells. This excess is then extracted and processed for human use.One of the widely used techniques for royal jelly production is the Doolittle grafting method, developed by Charles Doolittle.

Equipment used: Artificial queen cups, spatulas, and a grafting tool.

Procedure:

1. **Hive Selection:**Based on their strength and health. The chosen hives should have a large population of nurse bees, be free from diseases and pests, and have an abundant supply of pollen and nectar, which is crucial for colony development.
2. **Preparation of Artificial Queen Cups:**These cups are made from beeswax, usually ten per bar. If a hive has three frames, then 30 cups are recommended. A small drop of diluted royal jelly is placed in each cup to keep the larvae moist and to create a suitable environment for their development.
3. **Grafting Larvae:** Select worker bee larvae that are approximately 24 hours old. Using a grafting tool, carefully transfer each larva into a prepared queen cup.
4. **Colony Setup:** Place the frames with grafted larvae into queenless colonies. In the absence of a queen, nurse bees are stimulated to feed large quantities of royal jelly to the larvae in these cups.
5. **Jelly Harvesting:** After exactly three days, the larvae are removed from the cups, and the accumulated royal jelly is carefully collected using a spatula.

Precautions

Royal jelly is highly perishable and sensitive to air, light, and heat. Exposure to air can lead to oxidation and discoloration. Therefore, it should be stored in airtight containers. To protect it from light and maintain its quality, dark-colored glass jars are recommended.Immediately after collection, royal jelly should be kept under cold conditions. Under refrigeration (0-5°C), it can be preserved for up to 18 months. When stored at -17°C, its shelf life extends up to 24 months. Additionally, royal jelly can be preserved using advanced techniques such as lyophilization (freeze-drying), encapsulation, and nanoparticle coating, which help retain its nutritional and medicinal properties for longer periods.

Bee venom products and processing (Bogdanov, 2016)

Bee venom (apitoxin) production by worker bees is highest during the first 2 to 3 weeks of their lives. The venom sac capacity of a worker bee is about 0.3 mg. A single sting contains approximately 100 µg of dry bee venom, and around 10,000 bees are required to produce 1 gram of dry venom.Bee venom possesses several medicinal properties, including antiarthritic, antiviral, anticancer, antimetastatic, neuroprotective, antimicrobial, antioxidant, anti-inflammatory, cytoprotective, antihepatotoxic, antinociceptive, and radioprotective effects.It is exclusively used in therapies for treating immune-related and chronic diseases. Various forms of bee venom therapy include Bee

Sting Therapy (BST), Injectable Bee Venom Therapy (BVT), Topical Bee Venom Therapy, Advanced Pharmacopuncture Methods, Polymeric Bee Venom Therapy, and Oral Enteric-Coated Bee Venom Therapy. Most apiarists use the electric bee venom collection technique developed by Markovic and Mollnar in 1954.

Equipment required : A bee venom collector consists of a battery (24 to 30 volts), a transformer (with an impulse frequency of 50 to 1000 Hz and an impulse duration of 3 to 6 seconds), and a collector frame, which includes an electric wire net positioned above a glass plate.

Procedure:

1. **Placement of the Collection Device**: Keep the bee venom collector either at the entrance of the beehive or inside. Placement in such a way that allows for maximum contact between the bees and the wire grid.
2. **Power Supply:** Turn on the device to deliver an electric current of 24 to 30 volts through the wires of the collection frame.
3. **Bee Stimulation**: As bees come into contact with the electrified wires, they receive a mild shock. This irritation prompts them to sting the surface beneath the wires.
4. **Venom Deposition on the Glass Plate**: When stinging, the bees release venom onto the glass plate situated beneath the wire mesh. Unlike normal stinging events, the stinger is not detached from the bee during this process, ensuring their survival.
5. **Drying of the Venom**: Once exposed to air, the venom naturally dries and forms a yellowish-brown, crystalline layer on the glass plate.
6. **Collection of Dried Venom**: The dried venom is carefully scraped from the glass using a sterile spatula or blade and stored appropriately for preservation and later use.

Precautions

To minimize stress on bees and maintain overall colony productivity, the venom collection device should be operated with caution, ideally for only 15 to 20 minutes, and no more than three to four times a month. While this process may cause a slight reduction in honey yield (approximately 10 to 15%), limiting collections to just a few sessions per season generally has no significant impact on hive health or performance. Bee venom is highly sensitive to environmental conditions such as light, heat, and oxidation, requiring careful handling and storage. When kept at room temperature (25-30°C), it remains viable for up to three weeks. Under refrigerated conditions (4°C), it can be preserved for about three months, while deep freezing at -20°C enables safe storage for as long as five years, without compromising its therapeutic properties.

Propolis products and processing

Propolis contains around 300 bioactive compounds, including phenolic acids, flavonoids (such as flavones, flavanones, stilbenes, and chalcones), as well as steroids and lignans. It is well known for its antimicrobial, anti-inflammatory, antioxidant, and anticancer properties. Due to these benefits, propolis is widely used in various commercial and health-related products like toothpaste, skin creams, healing salves, syrups, and tinctures.

Equipment Required: Propolis Trap (A thin, flexible plastic sheet designed with narrow slits to encourage bees to fill gaps with propolis).

Procedure

1. **Installing the Propolis Trap:** Obtain a propolis trap and remove both the inner and outer covers of the beehive.

2. **Placement:** Place the propolis trap in the position of the inner cover, ensuring it fits securely.
3. **Adding Logs:** Place small wooden logs on top of the propolis trap to create space.
4. **Replace Outer Cover:** Reattach the outer cover above the logs. This setup allows light and air to enter the hive, which prompts bees to seal the openings using propolis.
5. **Collection Timing:** After 20 to 30 days, remove the trap and place it inside a polythene bag. Store it in a freezer at -18°C for 24 to 48 hours.
6. **Extraction:**Freezing makes the propolis brittle. By flexing the trap or tapping it with a hard tool, the brittle propolis can be easily removed.

Precautions

Adequate care should be taken to remove any wax or other unwanted hive materials from raw propolis during collection. To ensure high quality, propolis should be stored in a cool and dark environment. While preparing tinctures, ethanol with 70% purity is generally preferred as the extracting solvent. Propolis may be used in its raw state or ground into a fine powder before processing. It is often mixed in various solvents, such as ethanol, water, or edible oils like coconut, sunflower, or olive oil, to create tinctures and extracts that are commonly used for medicinal purposes.

Conclusion

Correct dissemination of knowledge about the uses and importance of bee byproducts such as royal jelly, bee venom, and propolis to the beekeepers, combined with transformation of quality information about the extraction of bee byproducts, followed by processing and creating good market channels, will help in increasing the income generation from the apiaries by beekeepers.

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PROSPECTS OF ZEOLITE IN MODERN AGRICULTURE

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Abstract

Farming with Zeolites-a group of hydrated naturally occurring aluminosilicates—offers notable solutions to many challenges facing modern agriculture, such as rapid urbanization, climate variability, water scarcity, and degrading soil quality, particularly as food demand rises with global population growth. Zeolites may benefit plant development and productivity from an agronomic stand point. Zeolite can hold nutrients in the root zone for plants to use when required. Application of zeolite along with chemical fertilisers could improve soil N, P, and K content, which supports sustained plant growth and reduces environmental pollution from leaching. Zeolites have the ability to alter the structure and texture of soil, which can have an immediate effect on the hydrological parameters of the soil such as water holding capacity, infiltration rate, saturated hydraulic conductivity because of their intricate internal structure and cation exchange capacity. To explore the use efficiency and beneficial role of zeolite, this research article truly highlights all the dynamic of it's multipurpose use to meet the increasing demand of food production with lower environmental impact.

Introduction

The word "zeolite" indicates a crystalline, hydrated aluminosilicate of alkali and alkaline earth cations forming an infinite, open, three-dimensional structure (Nakhil *et al.,* 2017). The general empirical formula is $M_2nO.Al_2O_3.xSiO_2.\ yH_2O$ Where, M represents any alkali or alkaline earth cation for example magnesium (Mg), sodium (Na), and potassium (K)), n the valence of the cation, x varies between 2 and 10, and y varies between 2 and 7, with structural cations comprising of Si, Al and Fe^{3+}. The pores and interconnected voids are occupied by exchangeable cations like Na^+, K^+, Ca^{2+} and water molecules thus making zeolites an extremely effective ion exchanger. The pore diameters are around 12 angstroms (Å); the pores are interlinked with channels about 8Å in diameter; rings of approximately 12 linked tetrahedrons compose these cages (Smedt *et al.,* 2015).

Zeolites represent a framework where some silicon atoms (Si) in tetrahedral coordination are substituted by aluminium atoms (Al) that introduces a negative charge to the lattice because aluminium has a lower valence (+3) compared to silicon (+4). The negative charge is balanced by exchangeable cations where the cations are not strongly bonded to the framework but are rather weakly bound to this anionic lattice-the negatively charged aluminate sites. Because of this weak binding, the cations can be "exchanged" with ions from the surrounding environment, which is the basis for the well-known cation exchange property of zeolites.

Key Properties of Zeolites

i. **Microporosity and Molecular Sieving:** Shows excellent molecular sieving properties possess uniform micropores with diameters typically ranging from about 0.3 to 1.0 nanometres. This pore structure allows zeolite to selectively adsorb molecules based on size and function effectively as molecular sieves.

ii. **Ion Exchange Capacity:** The charge imbalance due to the presence of aluminium in the zeolite framework determines the ion-exchange property of zeolites and is expected to induce potential acidic sites. Cation exchange capacity (CEC) of natural zeolites ranges from 100 to 200 cmol (+) kg^{-1}(Inglezakis *et al.*, 2015). Several factors like the negative charge of its framework structure, concentration, size, and charge of the exchange ions determine the exchange capacity of the zeolite.

iii. **Thermal and Chemical Stability:** Zeolites exhibit high physical and chemical stability due to strong covalent bonding in the aluminosilicate framework. Their stability varies with Si/Al ratio; high-silica zeolites are stable up to ~1300° C, whereas low-silica zeolites may degrade at around 700°C.

iv. **Hydration and Dehydration:** Containing water inside their pores, which can be reversibly lost upon heating without collapse of the framework, allowing for reversible dehydration and rehydration.

v. **Acidity and Catalytic Activity:** High-silica zeolites with H^+ exchange sites function as solid acid catalysts, capable of protonating hydrocarbons. The acidity increases with the Si/Al ratio, enhancing catalytic power in processes like fluid catalytic cracking in the petrochemical industry.

vi. **Adsorption:** They have high specific surface areas (several hundred m^2/g) and can adsorb both polar and nonpolar molecules. Zeolites rich in alumina tend to be more hydrophilic and attract polar molecules like water, while silica-rich zeolites are more hydrophobic and adsorb nonpolar molecules such as hydrocarbons.

Classification of Zeolite

The Si/Al ratio of zeolite also plays an important characteristic of zeolites. The Si/Al ratio is inversely proportional to the cation content, however directly proportional to the thermal stability. Based on Si/Al Molar ratio Zeolites are classified into three categories-

a) Low silica zeolites: Si/Al < 2
b) Intermediate silica zeolites: Si/Al between 2 and 5
c) High silica zeolites: Si/Al > 5

Type of Natural Zeolites used in Agriculture

It was reported that of more than 48 natural zeolites species known, the most well-known ones are clinoptilolite, erionite, chabazite, heulandite, mordenite, stilbite, and phillipsite (Polat *et al*., 2004). Natural zeolites, primarily clinoptilolite, are widely used in agriculture due to their crystalline, porous aluminosilicate structure, which provides unique benefits for soil and plant health. Clinoptilolite has a high cation exchange capacity and a great affinity for NH4+ ions (Inglezakis, 2004) by that, of the 40 naturally occurring zeolites studied by research groups.

The key Benefits of Zeolite in Agricultural Aspects

Improvement in Nutrient Retention:

Zeolites act like microscopic sponges with high porosity and cation exchange capacity, which allows them to retain essential nutrients in the soil. A gradual increase in the adsorption of N, P, and K was observed by Shin *et al*. (2021), with the increasing equilibrium concentration (Ce). Amendment of clinoptilolite zeolite to sandy soils has been reported to lower leaching loss of nitrogen, increases moisture and nutrients in the soil due to increased soil surface area and cation-exchange capacity (He *et al*., 2002). Zeolite addition (5 tonnes ha^{-1}) along with manures improved potassium availability and uptake in soybean cultivated in Alfisols (Haniati *et al*., 2019**)**. Application of zeolite also improved N availability and uptake in soybean (Triatmoko *et al*., 2019). Shin *et al*. (2021**)** reported that zeolite-based adsorbents showed the maximum K sorption to the extent of 40-42 mg g^{-1} by natural zeolite and treated zeolite.

Soil Moisture Retention:
Zeolites have several positive effects on soil properties, such as increasing soil moisture, promoting hydraulic conductivity thus they are widely used as soil conditioners to improve soil physio-chemical properties. Natural zeolites are extensively used to improve soil physical environment, particularly in sandy and clay poor soils (Abdi *et al*., 2006). Zeolite improves soil structure by enhancing aeration in heavy clay soils and increasing cohesion in sandy soils. Zeolites possess higher water holding capacities (Ravali *et al.,* 2020) by altering the total porosity, pore size distribution, pore channel connectivity, and tortuosity of soils.

Environmental Remediation:
Zeolites help stabilize soil pH and act as natural buffers, promoting optimal nutrient availability. Zeolites, have a high cation-exchange capacity, and they attract positive-charged ions; therefore, zeolites are widely used for cationic pollutants' sequestration, such as heavy metals: Cd, Pb, Cr, Zn, Cu, etc. Research states (Zwolak *et al.,* 2019) that low soil pH (acidic conditions) is indeed a primary determinant of heavy metal solubility in soil; increasing their bioavailability and becomes potential threat to enter into the food chain. Zeolite with their ability to adsorb heavy metals and pollutants from contaminated environments reduces bioavailability of toxins to plants, supporting soil and crop health. Many authors demonstrated the high affinity of natural zeolites to heavy metals (Tashauoei *et al*, 2010).

Slow-Release Fertilizer Carrier:
Zeolites are used as carriers for fertilizers, pesticides, and herbicides. Their high ion-exchange capacity allows controlled release of nutrients and chemicals, improving the efficiency and reducing environmental runoff of these agrochemicals. Natural zeolites, due to their structure and properties, inert and nontoxic material can be used as a slowly releasing carrier of fertilizer (Rehakova *et al*., 2004). Zeolites slowly release these nutrients close to plant roots, enhancing nutrient use efficiency, reducing fertilizer leaching, and improving crop growth (Sangeetha *et al*., 2016).

Crop Yield and Quality Enhancement:
Application of zeolites has been shown to improve crop yields and enhance the nutritional quality of fruits and vegetables. They also help plants better resist diseases and environmental stresses. Cairo *et al*. (2017) reported that treatment Zeolite 7.5 t ha^{-1} + Sugarcane Filter Cake (SFC) 22.5 t ha^{-1} showed the best result in Sugarcane production.

Use in Animal Feed and Pest Control:
Besides soil use, zeolites are applied in animal husbandry as dietary supplements and for odor control, and as inert dust for stored-pest management in agricultural products. Natural zeolites and some clay minerals have proven to be effective in protecting animals against mycotoxins (Feliczak-Guzik, 2018).The apparent ability of clinoptilolite and other zeolites to absorb aflatoxins that

contaminate animal feeds has resulted in measurable improvements in the health of swine, sheep, and chickens.

Conclusions

In summary, Zeolites by improving soil physical and chemical properties, promoting cleaner environments, and enhancing resource efficiency, zeolites help achieve a balanced, resilient agricultural ecosystem that embodies sustainable agriculture goalsunder intensive farming systems and climate change challenges. These benefits position zeolites as promising tools for enhancing agricultural productivity while protecting environmental health. Zeolites find a large number of potential applications in agriculture, particularly in soil and water management. They can be used as either carriers of nutrients or medium to free nutrients to promote nutrient use efficiency. They serve as effective carriers and slow-release agents of nutrients, enhancing nutrient use efficiency and reducing fertilizer losses. Further interdisciplinary research spanning mineralogy, soil science, chemistry, biology, and agricultural engineering is necessary to optimize applications and support profitable, sustainable use of zeolites in agriculture.

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NATURE'S CARBON VAULTS: WETLANDS AS STABILIZERS OF THE ATMOSPHERIC CARBON CYCLE

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Abstract

One of the most important aspects of Earth's ecology is wetlands. Since they filter substances and keep water pure, they are commonly referred to as the "kidneys of the environment." One of the most robust and well-balanced biological systems on the planet is a result of the abundance of species present in these diverse habitats.

In addition to their ecological value, wetlands also help regulate the climate by serving as natural carbon sinks. With increasing carbon dioxide levels in the atmosphere, their ability to store carbon makes them a realistic solution for reducing the impacts of climate change. This article looks at the various functions of wetlands, highlighting their role in ecological stability and carbon balance. It also argues for their protection and careful use in environmental policy and conservation efforts.

Keywords: Atmospheric carbon, Carbon Sequestration, Environment, Wetland.

Introduction

Wetlands are essential to the survival of human life. With their abundance of life and biodiversity, these ecosystems rank among the richest on Earth. Numerous plant, animal, and aquatic species are supported by these dynamic natural ecosystems, which also supply essential water resources. They are therefore essential to survival and ecological balance. The primary determinant of soil growth and the kinds of plant and animal communities that inhabit and depend on it in these regions is water saturation (Nag *et al*., 2020).

The Ramsar Convention adopts a broad definition of wetlands, covering diverse ecosystems such as lakes, rivers, underground aquifers, swamps, marshes, wet grasslands, peatlands, oases, estuaries, deltas, tidal flats, mangroves, and other coastal habitats. It also covers human-made sites like fish ponds, rice paddies, reservoirs, and salt pans.

Wetlands are land areas that have water on them. They are created by floods, such as floodwater (either continuous or sporadic), high tides along the coast, or water flowing from an aquifer or spring. Between land-based and water-based ecosystems, these are the transitional zones.

Wetlands as Natural Regulators of Atmospheric Carbon

Wetlands are one of the most productive ecosystems in the biosphere, similar to tropical evergreen forests. They play a crucial role in the ecological health of a region. Wetlands like peat lands, mangrove forests, salt marshes, and sea grass beds store 20% of the planet's organic carbon, even though they only cover 1% of the Earth's surface (Vijay *et al.,*2017).

Carbon Sequestration Mechanisms in Wetlands

Wetlands effectively trap and store carbon, making them crucial in combating climate change. Because of their special structure, they may absorb and retain carbon dioxide through a variety of chemical and biological processes, forming a stable carbon reservoir over an extended length of time. Many aquatic plants, such as floating pond lilies, cattails, cypress, tamarack, and blue spruce, as well as algae, fish, shellfish, insects, and carnivorous animals, such as dragonflies, otters, alligators, and osprey, as well as numerous migratory birds and waterfowl, can be found in wetlands (Santos *et al*., 2025).

Wetland vegetation uses photosynthesis to absorb carbon dioxide from the atmosphere. Carbon is stored in plant tissues by this mechanism, which promotes the increase of biomass. The oxygen content of the wet soils and sediments is low. Because organic matter breaks down more slowly in an anoxic environment, carbon-rich molecules can build up rather than return to the atmosphere.

Maintaining soil saturation, which delays the decomposition of organic matter and helps maintain carbon in the ecosystem, is a critical function of hydrology. Furthermore, the type and depth of the wetland affect its greenhouse gas emissions, and microbial activity in the wetland controls the cycling of carbon dioxide and methane.

Together, these processes show that wetlands are not just passive storage areas; they actively help manage atmospheric carbon levels. Preserving and rehabilitating wetlands is crucial for boosting global carbon storage and lessening the harmful impacts of climate change.

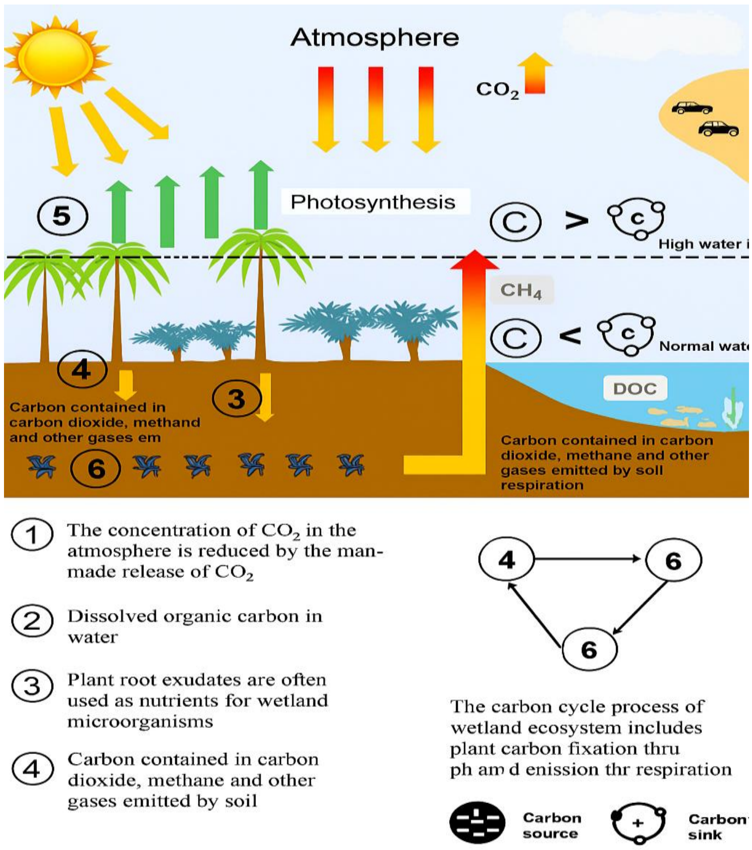

Fig. 1 : Carbon cycle in the wetland ecosystem.

Under Siege: The Alarming Decline of Global Wetlands

One of the most significant and fruitful ecosystems on the planet is wetlands. They are essential to maintaining the equilibrium of aquatic habitats. They act as carbon sinks, biodiversity repositories, flood controllers, and natural water filters. Wetlands are becoming more and more threatened by human activity, notwithstanding their significance. As a result, they have deteriorated and their services have been lost. Globally, wetlands are vanishing three times as quickly as forests.

The ecological health and environmental services of wetlands are reduced as a result of a combination of natural and human-caused events (Das *et al*., 2025). Wetlands are contaminated by human activities such as industrial discharge, agricultural runoff, and overuse of pesticides and fertilizers. Aquatic life is harmed and eutrophication is the result. Because concrete infrastructure diminishes green cover, the atmosphere's concentration of greenhouse gasses rises. Industrial and sewage effluent contaminate wetlands' pristine water, endangering aquatic life and triggering a number of illnesses.

This results in eutrophication and harms aquatic life. Concrete infrastructure reduces green cover, causing an increase in greenhouse gases in the atmosphere. Industrial wastewater and sewage pollute the clean waters of wetlands, endangering human health, spreading diseases, and damaging aquatic ecosystems (Radhakrishnan*et al.,*2025).

The situation is also exacerbated by natural forces. Increased evaporation and decreased water levels in wetlands are caused by climate change's effects on temperature and precipitation patterns. The hydrological balance is upset, and carbon storage is impeded. Sedimentation, invasive species, and disruptions in nutrient cycling exacerbate the problem by lowering the resilience and habitat quality of wetland areas. All of these elements contribute to a considerable reduction in wetland size and function, endangering the services they provide for water purification, carbon management, and biodiversity. Therefore, in order to address the effects of climate change and preserve ecological stability, it is imperative that wetlands be preserved and restored.

Analyse trends

Topic	Details	Key Highlights
Blue Carbon	Carbon captured and stored by coastal and marine ecosystems.	Coastal ecosystems act as powerful natural filters.- Remove CO_2 from the atmosphere.- Store carbon in waterlogged soils and dense vegetation for hundreds to thousands of years.- Play a vital role in slowing climate change.
Healthy Oceans & Carbon Binding	Oceans store a major share of the world's biological carbon.	55% of all biological (green) carbon is captured by marine organisms, not land plants.- Known as "Blue Carbon" due to its marine origin.- Healthy oceans are essential for maintaining this process.
Carbon Sinks in Wetlands	Wetlands accumulate organic matter in soils and sediments, acting as carbon sinks.	Decomposition rates are shaped by climate conditions—such as temperature and moisture—and the quality of organic matter, with saturated, low-oxygen environments slowing the process and enabling wetlands to be among the most effective ecosystems for long-term soil carbon storage.

Conclusion

Wetlands are not just important ecosystems; they also help protect our climate. Even though they cover a small part of the Earth's surface, they store a significant amount of organic carbon, making them crucial in the fight against global warming. Their special water systems, variety of plant and animal life, and soil processes enable them to capture carbon for centuries. However, rapid urban development, pollution, and changes in land use put them at risk.

To maintain their role as natural carbon storages, we need to act quickly with restoration efforts and new policies. By including wetlands in climate plans and recognizing their potential for storing blue carbon, we can create a solution that benefits both people and nature.

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CLIMATE-SMART STRATEGIES FOR PRODUCTIVE AND RESILIENT FARMING: FUTURE PERSPECTIVE

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Climate-smart agriculture (CSA) and climate-resilient agriculture (CRA) are both approaches to farming that aim to address the impacts of climate change, but they differ in their focus and scope. CSA is a broader approach that seeks to transform agri-food systems to be more sustainable and resilient focusing to sustainably increase agricultural productivity and incomes, adapt to climate change, and reduce greenhouse gas emissions where possible. In essence, CSA is a vision for a more sustainable and resilient agricultural future, while CRA is a set of practical tools and strategies for achieving that vision in the face of climate change which focuses on specific practices that help farmers cope with climate change impacts. In essence, CSA is a vision for a more sustainable and resilient agricultural future, while CRA is a set of practical tools and strategies for achieving that vision in the face of climate change.

Climate resilience strategies help build the capacity of communities, ecosystems and economies to adapt to changing conditions and recover from climate-related shocks. The three pillars of climate-smart agriculture are: (1) sustainable productivity with focus to improving agricultural productivity in a sustainable manner (2) adaptation to climate change to building resilience to the impacts of climate change and (3) mitigation of greenhouse gas emissions:

Climate change is increasingly seen as the major threat to the food security and sustainability of agriculture in India. Keeping in view of the importance of this problem, Indian Council of Agricultural Research initiated a National Network project on 'Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change'. The nation-wide network project, first of its kind in ICAR, was started in 2004 during the X Plan with 15 Institutes which was increased to 23 in XI Plan (2007-2012). These institutes/universities covered all major sectors of agriculture viz., crops, horticulture, plantations, live-stock, inland and marine fisheries, poultry and natural resources like water and soil.

Past trends in climate

Analysis of the long-term series of annual rainfall data from 1140 rain gauge stations across the country indicated significant negative trends in the eastern parts of Madhya Pradesh, Chhattisgarh and parts of Bihar, Uttar Pradesh, parts of northwest and northeast India and in a small part of Tamil Nadu. However, significant increasing rainfall trends have been noticed in Jammu and Kashmir and in some parts of southern peninsula 2. Analysis also indicated increasing trends in annual rainfall, and minimum temperature in parts of Bihar, West Bengal and Gujarat. In Punjab, the annual and seasonal minimum temperature has increased over the past three decades in the range of 0.02-0.07 o C/year. Analysis on mean annual temperature at 47 locations spread across the country indicated an increasing trend in the central and southern parts and north eastern region. While decreasing trends were observed in some parts of Gujarat, Konkan region, north-western parts of Madhya Pradesh and Eastern Rajasthan. The analysis of past 108 years rainfall data at Ludhiana revealed that the annual, monsoon and summer season rainfall has increased. In Andhra Pradesh, the percentage of occurrence of droughts was more during 1971-1980 and 1991-2000 decades when compared to 1981- 1990 decade in all agro-climatic zones except in southern and in scarce rainfall zones.

Trends in extreme weather events

Analysis of occurrence of extreme weather events during past six decades indicated an increasing trend in maximum one-day precipitation in the west coast of Maharashtra, south Madhya Pradesh, east Bihar, Assam, north and west Karnataka, eastern Uttar Pradesh, western Jharkhand and Ganga Nagar area of Rajasthan. On the other hand, a declining trend was observed in parts of southern Karnataka, western Maharashtra, northern Chhattisgarh, northern Madhya Pradesh, and western Uttar Pradesh.

The frequency of occurrence of cold days during the past five decades significantly declined in north western Madhya Pradesh, southern Chhattisgarh, western Gujarat and in parts of peninsular India. Frequency of occurrence of cold nights declined in major parts of north India, south and west Gujarat, west Maharashtra, coastal Andhra Pradesh, southern Karnataka, north western Tamil Nadu and northern Kerala. On the other hand it increased in north Chhattisgarh and northern Jammu and Kashmir states.

The frequency of occurrence of warm days significantly increased in parts of southern Rajasthan, western Madhya Pradesh, western Gujarat, northern Jammu and Kashmir and Manipur, while it declined in parts of West Bengal, Jharkhand, southern Bihar, eastern Himachal Pradesh, Uttarakhand, north western Uttar Pradesh and northern Haryana. In peninsular India, frequencies of warm days increased except in north and eastern Andhra Pradesh, southern Tamil Nadu, northern Karnataka and in south and north of Maharashtra.

Greenhouse gas emission from Indian agriculture

The inventory of greenhouse gas (GHG) emission for the year 2007 indicated that Indian rice fields covering an area of 43.86 million hectares emitted 3.37 million tons of CH4. Total N2 O emission from agricultural soils of India was 0.22 million tons. Burning of crop residues in fields emitted 0.25 million tons of CH4 and 0.01 million tons of N_2O. The inventory of greenhouse gas (GHG) emission for the year 2007 indicated that Indian rice fields covering an area of 43.86 million hectares emitted 3.37 million tons of CH_4. Total N_2 O emission from agricultural soils of India was 0.22 million tons. Burning of crop residues in fields emitted 0.25 million tons of CH4 and 0.01 million tons of N_2O.

2Agricultural soils emitted 16% of the total CO_2 eq. emission from agriculture and 20% of the emissions were from rice cultivation. Emission of GHG from agriculture in different states showed that Punjab, Haryana, Uttar Pradesh and Andhra Pradesh emitted higher amount of N_2O-N because of higher amount of N fertilizer use. States such as West Bengal, Andhra Pradesh, Odisha, Bihar, Jharkhand and north eastern states emitted higher amount of methane per hectare of rice cultivation.

Emission of methane from Indian rice fields has remained almost constant since 1980. Emission of nitrous oxide, however, is increasing as a result of higher use of nitrogenous fertilizer over the years. Total GWP (methane x 25 + nitrous oxide x 298) of Indian agriculture per unit area (kg CO_2 eq. ha-1) is, therefore, increasing. However, GWP per unit of produce (kg CO_2 eq. ton-1) is decreasing.

Similarly, GHG intensity per unit agricultural gross domestic product (Ag-GDP) also declined over the years. This decline was due to increase in agricultural production of the country because of adoption of high yielding crop varieties and better crop management practices without increase in area under agriculture.

An inventory of enteric methane emission for 2006 was prepared following IPCC guidelines on good practice guidance and uncertainty reduction and using Tier 2 methodology of IPCC. Tier 1 methodology and default factors of IPCC have been used for estimating enteric methane emissions for sheep, goats, equines, pigs and other animals. The emissions for the year 2006 were estimated at 9.39 Tg. year-1 from both enteric emissions and manure management. The contribution of indigenous cattle to enteric emission was 38% and that of buffaloes was 43%.
It is estimated that annual CO_2 emission of marine fishing boats in India was 3.6 million tons during 2005-2007. The mechanized boats emitted 1.67 tons of CO_2 per ton of fish catch, while motorized boats with outboard engine emitted 0.48 t CO_2 per ton of fish catch. Among the mechanized craft, the trawlers emitted more CO_2 than the gillnetters and dolnetters. Based on the data available on the number and size of fishing boats in India in the past years, it is estimated that CO_2 emission per ton of fish caught has increased by 64% in a period of 25 years.

Climate-Smart Agriculture vs Conventional Farming
Here's a detailed **comparison table of Climate-Smart Agriculture (CSA) vs Conventional Farming** showing how CSA differs in approach, practices, and outcomes:

Table Comparison of Climate-Smart Agriculture vs Conventional Farming

Aspect	Conventional Farming	Climate-Smart Agriculture (CSA)
Primary Goal	Maximize yields and short-term productivity	Ensure productivity **while enhancing resilience** to climate change and reducing emissions
Approach to Climate	Climate is considered static; farming practices do not account for variability	Farming systems designed to adapt to **climate variability, extreme events, and long-term change**
Resource Use	Often inefficient use of water, fertilizers, pesticides, and energy	Focuses on **efficient resource use**, precision farming, integrated nutrient and water management
Soil Management	Heavy tillage, monocropping, and chemical inputs often degrade soils	Promotes **soil health** through conservation tillage, organic matter addition, crop rotation, and cover crops
Water Use	Over-irrigation, groundwater depletion common	**Efficient water management** (drip irrigation, rainwater harvesting, micro-irrigation, deficit irrigation)
Crop Diversity	Reliance on monocultures (e.g., rice–wheat system)	Promotes **crop diversification, intercropping, agroforestry** for resilience

Aspect	Conventional Farming	Climate-Smart Agriculture (CSA)
Carbon Footprint	High GHG emissions (methane, nitrous oxide, CO_2) from fertilizers, paddy fields, livestock	***Mitigation-oriented***: reduced emissions, carbon sequestration, low-emission livestock practices
Technology Use	Limited reliance on modern ICT tools; often traditional methods	Uses **ICT, remote sensing, climate forecasting, precision farming tools**
Risk Management	Reactive—farmers suffer heavy losses during droughts, floods, or pests	Proactive**—climate advisories, crop insurance, resilient crop varieties, early warning systems**
Economic Focus	Short-term profit maximization, often at environmental cost	Long-term **sustainability, profitability, and livelihood resilience**
Biodiversity	Low biodiversity, ecosystem simplification	Promotes **ecosystem services, pollinators, beneficial insects**
Policy Support	Focused on subsidies for inputs (fertilizers, power, water)	Support for **resilience, carbon credits, climate financing, ecosystem services payments**
Outcome	Higher yields in the short run but declining soil fertility, water stress, and vulnerability to climate shocks	Sustainable yields, **enhanced resilience, reduced vulnerability, and contribution to climate mitigation**

Benefits of climate resilient agriculture in continuous sentence form

Climate-resilient agriculture provides multiple benefits as it helps farmers sustain and even increase crop productivity under changing climatic conditions, reduces vulnerability to droughts, floods, and heat stress, conserves soil health and fertility through sustainable land management practices, promotes efficient use of water and nutrients thereby lowering production costs, diversifies income sources through mixed cropping and agroforestry systems, enhances biodiversity and ecosystem services, reduces greenhouse gas emissions while increasing carbon sequestration, improves food and nutritional security for farming communities, strengthens rural livelihoods by making them less dependent on weather extremes, supports long-term sustainability of natural resources, and creates opportunities for farmers to access climate finance, carbon credits, and green markets, thus contributing not only to individual resilience but also to national food security and global climate mitigation efforts.

Benefits of Climate-Resilient Agriculture (CRA) into **economic, environmental, and social categories** are given below**:**

1. Economic Benefits

- Ensures **stable and sustainable crop yields** despite climate variability.
- Reduces **input costs** through efficient use of water, fertilizers, and energy.
- Diversifies farmer income through **crop diversification, agroforestry, and integrated farming systems.**
- Minimizes crop losses by **adopting climate-resilient varieties** and risk-reducing practices.
- Enhances farmer access to **climate finance, crop insurance, carbon credits, and premium green markets.**
- Improves long-term **farm profitability and livelihood security.**

2. Environmental Benefits

- Conserves **soil fertility and structure** through reduced tillage, organic amendments, and cover cropping.
- Promotes **efficient water use** via rainwater harvesting, drip irrigation, and groundwater recharge.
- Enhances **biodiversity and ecosystem services**, including pollination and natural pest control.
- Reduces **greenhouse gas emissions** from agriculture (methane, nitrous oxide, CO_2).
- Increases **carbon sequestration** in soils and biomass through agroforestry and conservation farming.
- Helps in **sustainable natural resource management** for future generations.

3. Social Benefits

- Strengthens **food and nutritional security** for farm families and communities.
- Builds **resilience of rural livelihoods** against climate shocks like droughts, floods, and heatwaves.
- Empowers farmers with **knowledge, ICT tools, and climate advisories** for better decision-making.
- Encourages **community participation, cooperatives, and collective action** in climate adaptation.
- Reduces **migration pressures** by making agriculture more viable and sustainable.
- Improves **health and well-being** through reduced chemical inputs and diversified nutritious food production.

In summary, **Climate-Resilient Agriculture provides a triple win ie. higher and stable productivity** (economic gain), **reduced environmental footprint** (ecological sustainability), and **stronger adaptive capacity** of farming communities (social resilience).

Impacts of Climate Change on Agriculture

Climate change is projected to reduce the timely sown irrigated wheat production by about 6% in 2020 scenario from existing values. When late and very late sown wheat also is taken into consideration, the impacts are projected to be about 18% in 2020, 23% in 2050 and 25% in 2080 scenarios, if no adaptation measures are followed. However, adaptation to climate change by sowing improved varieties and employing improved input efficiency technologies coupled with application of additional nitrogen can not only offset the negative impacts, but can also improve the net yields by about 10% in 2020. However, in 2050 scenario, such adaptation measures marginally improve yields while in 2080 scenario the wheat yields are projected to be vulnerable by about 6% in spite of above adaptation strategy, thus making it necessary to develop input use efficiency technologies and 'region specific adverse-climate tolerant varieties.

On an aggregated scale, in climate scenarios of MIRO and PRECIS, the irrigated rice yields are projected to reduce by ~4% in 2020, 7% in 2050 and by ~10% in 2080 scenarios. On the other hand, rainfed rice yields in India are likely to be reduced by ~6% in 2020 scenario, but in 2050 and 2080 scenarios they are projected to decrease only marginally (central India (Maharashtra and Madhya Pradesh) also are projected to face >5% of yield loss. Adopting improved varieties with improved input efficiency and providing 25% of additional nitrogen can not only offset the climate change impacts but also can improve the production by 6-17% in irrigated conditions and by about 20 to 35% in rainfed condition in future climate scenarios.

Adaptation strategies such as improved and tolerant variety managed under improved input efficiency with additional nitrogen fertilizer can enhance the irrigated maize net production by about 21% in 2020, 10% in 2050 and 4% in 2080 scenarios. Rainfed sorghum yields, on all India scale, are projected to marginally (2.5%) decline in 2020 scenario while it is projected to decline by about 8% in 2050 scenario. Adaptation to climate change can not only offset the negative impacts but also can improve the yields by about 8% in 2020 scenario.

Global climate change may increase production of potato in Punjab, Haryana and western and central UP by 3.46 to 7.11% in 2030 scenario, but in rest of India, particularly West Bengal and southern plateau region, potato production may decline by 4-16%. It is primarily the mean minimum temperature during tuber growing period which affects potato yield.

The increase in temperature due to climate change may decrease harvest index (HI) in large parts of Maharashtra, parts of Karnataka and Andhra Pradesh. Analysis on the stress degree hours in winter potato growing regions showed that under the baseline scenario, most of the Indo-Gangetic plains region experienced 1000-to-5000-degree hours of stress due to a combination of both maximum and minimum temperatures. However, under climate change scenario the temperature stress increased further and the area with severe stress (9000-to-13000-degree hours) is projected to increase significantly in large parts of Maharashtra, Jharkhand, Odisha and Gujarat. Similarly, pockets with extreme stress (>13000-degree hours) are projected to increase.

The simulation results indicated that on an average, future climate would have a positive impact on productivity of rainfed soybean in the country. Increase in soybean yield in the range of 8-13% under different future climate scenarios (2030 and 2080) is projected. In case of groundnut, except in the climate scenario of 2080, which showed a decline of 5% in yield, rest of the scenarios showed 4-7% increase in rainfed yields as compared to the baseline. The maximum positive impact of future climate was observed on chickpea, which showed an average increase in productivity ranging from 23 to 54%. However, a large spatial variability for magnitude of change in the productivity is projected. The simulated rainfed yields of soybean and groundnut showed a strong positive association with crop season rainfall while that of chickpea yields were significantly associated with crop season temperature.

Government of India is aware about the impact of climate change on agriculture and farmers' lives. Extensive field and simulation studies were carried out in agriculture by the network centres located in different parts of the country. The climate change impact assessment was carried out using the crop simulation models by incorporating the projected climates of 2050 & 2080. In absence of adoption of adaptation measures, rainfed rice yields in India are projected to reduce by 20% in 2050 and 47% in 2080 scenarios while, irrigated rice yields are projected to reduce by 3.5% in 2050 and 5% in 2080 scenarios. Climate change is projected to reduce wheat yield by 19.3% in 2050 and 40% in 2080 scenarios towards the end of the century with significant spatial and temporal variations. Climate change is projected to reduce the *kharif* maize yields by 18 and 23% in 2050 and 2080 scenarios, respectively. Climate change reduces crop yields and lower nutrition quality of produce. Extreme events like droughts affect the food and nutrient consumption, and its impact on farmers.

Climate change impacts on Indian agriculture

Climate change significantly impacts Indian agriculture through various channels, leading to reduced crop yields, disruptions in farming practices, and potential food security challenges. Rising temperatures, erratic rainfall patterns, and extreme weather events like droughts and floods are major drivers of these impacts. Here's a more detailed look:

1. Direct Impact on Crop Yields:

- **Temperature Increase:** Higher temperatures can shorten crop growth cycles, reduce yields, and negatively affect the nutritional quality of crops. For example, a 2.5 to 4.9°C increase could reduce wheat yields by 41-52% and rice yields by 32-40%.
- **Altered Rainfall:** Changes in rainfall patterns, including droughts and floods, can damage crops, disrupt planting and harvesting, and reduce overall production.
- **Extreme Weather Events*:*** Floods, cyclones, and droughts can devastate crops and agricultural infrastructure, leading to significant losses.

2. Impact on Farming Practices:

- **Water Scarcity:** Climate change contributes to water scarcity, impacting irrigation and putting pressure on groundwater resources, which are heavily relied upon for agriculture.
- **Soil Degradation:** Intensive farming practices, coupled with climate change impacts, can lead to soil degradation, reducing its fertility and capacity to support crops.
- **Shifting Cropping Patterns:** Farmers may need to adapt by shifting to more climate-resilient crops or adjusting their planting schedules, but this requires access to information and resources.
- **Increased Pest and Disease Incidence:** Warmer temperatures and altered rainfall patterns can lead to increased outbreaks of pests and diseases, further impacting crop yields.

3. Impact on Food Security:

- **Reduced Food Production:** The combined effects of lower crop yields and disruptions to farming practices can lead to a decrease in overall food production, potentially impacting food security at the national and household levels.
- **Impact on Nutritional Security:** Climate change can also affect the nutritional value of crops, potentially reducing the availability of essential nutrients.
- **Increased Food Prices:** Lower food production and disruptions to supply chains can lead to increased food prices, impacting affordability and access to food, especially for vulnerable populations.

4. Impact on Farmers:

- ***Reduced Income and Livelihoods*:** Climate change impacts on agriculture can lead to lower incomes for farmers, potentially increasing their vulnerability and debt burden.
- ***Farmer Distress and Migration*:** Crop failures and economic hardship can lead to farmer distress, potentially driving rural-urban migration.

5. Regional Variations:

- **Eastern and Coastal Regions:** Regions like the eastern coast of India are highly vulnerable to cyclones and floods, causing significant damage to agriculture.
- **Western and Central India:** Droughts and water scarcity are major concerns in these regions, impacting crop production and livelihoods.

6. Need for Adaptation and Mitigation:

- **Developing Climate-Resilient Crops:** Research and development of crop varieties that are more tolerant to heat, drought, and other climate-related stresses are crucial.
- **Improving Water Management:** Adopting efficient irrigation techniques, promoting water conservation practices, and managing water resources effectively are essential.
- **Diversifying Crops and Farming Systems:** Promoting crop diversification and exploring alternative farming systems can help reduce the risks associated with climate change.
- **Strengthening Early Warning Systems:** Developing and implementing robust early warning systems for extreme weather events can help farmers prepare and minimize losses.
- **Promoting Sustainable Practices:** Encouraging sustainable agricultural practices, such as conservation tillage, integrated nutrient management, and agroforestry, can improve soil health and resilience.
- **Providing Financial Support and Insurance:** Providing access to crop insurance and other financial support mechanisms can help farmers cope with climate-related losses.

Climate-Smart Strategies for Productive and Resilient Farming

Climate-smart agriculture integrates practices like drought-resistant crops, efficient water management (drip irrigation, rainwater harvesting), soil conservation (no-till farming, cover crops, organic fertilizers), and agroforestry to boost productivity, build resilience against extreme weather, and reduce greenhouse gas emissions. Key strategies also include crop diversification, integrated pest management, precision farming technologies like GIS and GPS, and the use of renewable energy for farm operations. Here are some key climate-smart strategies:

- **Climate-Resilient Crop Management**
    - **Planting resistant varieties:** Use crop varieties that are tolerant to drought, heat, salinity, or floods to ensure stable yields.
    - **Crop diversification:** Grow a variety of crops to reduce the risk of complete crop failure from extreme weather and improve soil health.
    - **Optimizing planting times:** Adjust crop calendars to suit changing weather patterns.
- **Soil and Water Management**
    - **Efficient irrigation:** Implement drip irrigation and sprinkler systems for precise water delivery.
    - **Rainwater harvesting:** Collect and store rainwater for use during dry spells.
    - **Soil conservation:** Practice no-till or reduced tillage farming, use cover crops, and apply organic fertilizers to improve soil structure and water retention.
- **Sustainable Farming Practices**
    - **Agroforestry:** Integrate trees into farming systems to prevent soil erosion, provide windbreaks, and sequester carbon.
    - **Integrated Pest Management (IPM):** Use biological controls and natural predators to manage pests, reducing the need for chemical pesticides.
    - **Organic farming:** Utilize compost, manure, and green manures to improve soil fertility and build organic carbon.
- **Technology and Infrastructure**
    - **Precision agriculture:** Employ technologies like GIS, GPS, and remote sensing for precise application of inputs, improving efficiency.

  - **Digital advisory systems:** Use digital tools to provide farmers with crucial climate information and expert advice.
  - **Climate-resilient infrastructure:** Invest in storage facilities and transportation networks that can withstand extreme weather events.
- **Livestock Management and Renewable Energy**
  - **Climate-smart livestock production:** Adapt livestock management practices to improve productivity and resilience.
  - **Renewable energy:** Integrate solar, wind, and biogas for farm operations to reduce reliance on fossil fuels.

Government schemes/plans to make agriculture more resilient to climate change

Government of India has formulated schemes/plans to make agriculture more resilient to climate change.

- The National Mission for Sustainable Agriculture (NMSA) is one of the Missions within the National Action Plan on Climate Change (NAPCC). The mission aims at evolving and implementing strategies to make Indian agriculture more resilient to the changing climate.
- To meet the challenges of sustaining domestic food production in the face of changing climate, the Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India launched a flagship network research project 'National Innovations in Climate Resilient Agriculture' (NICRA) in 2011. The project aims to develop and promote climate resilient technologies in agriculture, which addresses vulnerable areas of the country and the outputs of the project help the districts and regions prone to extreme weather conditions like droughts, floods, frost, heat waves, etc. to cope with such extreme events.
- Short term and long-term research programs with a national perspective have been taken up involving adaptation and mitigation covering crops, horticulture, livestock, fisheries and poultry. The main thrust areas covered are;
  a. identifying most vulnerable districts/regions,
  b. evolving crop varieties and management practices for adaptation and mitigation,
  c. assessing climate change impacts on livestock, fisheries and poultry and identifying adaptation strategies. Since 2014, 1888 climate resilient varieties have been developed besides 68 location specific climate resilient technologies have been developed and demonstrated for wider adoption among farming communities.

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WASTE VALORIZATION AS A CLIMATE ACTION STRATEGY: PATHWAYS TO CARBON NEUTRALITY AND SDGS

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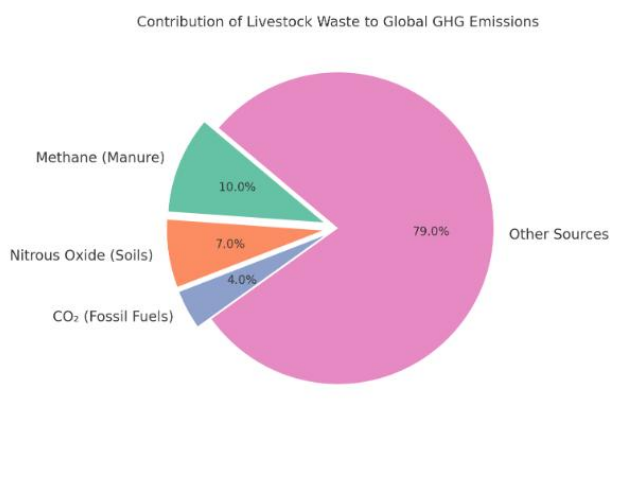
Abstract

The global livestock and agricultural sector generates vast amounts of organic waste in the form of animal dung, crop residues, food waste, and agro-industrial by-products. If unmanaged, these wastes release methane, nitrous oxide, and carbon dioxide—major greenhouse gases contributing to global warming. Waste valorization, using green technologies such as composting, anaerobic digestion, biochar production, and algae-based systems, offers a sustainable approach to transform waste into bioenergy, organic fertilizers, and bioproducts. These technologies not only reduce environmental pollution but also create renewable energy alternatives and carbon sinks, thereby serving as effective mitigation strategies against climate change. Moreover, they directly contribute to lowering the carbon footprint of agriculture and advancing multiple Sustainable Development Goals (SDGs).

Introduction

Global warming, driven largely by anthropogenic greenhouse gas (GHG) emissions, poses unprecedented threats to ecosystems, food security, and rural livelihoods. Agriculture and livestock together account for nearly 14.5% of total global GHG emissions, with methane from enteric fermentation and manure being dominant contributors (FAO, 2013). Waste valorization—converting waste into valuable products—provides a dual benefit: reducing emissions while generating renewable resources. The integration of green technologies into waste management is emerging as a climate-smart strategy to promote sustainable development.



Green Technologies for Waste Valorization

1. Anaerobic Digestion and Biogas Production

Animal manure and agro-residues can be fed into anaerobic digesters to produce biogas, a renewable energy source composed mainly of methane. This replaces fossil fuels for cooking and electricity, while the slurry acts as a biofertilizer. By capturing methane that would otherwise escape into the atmosphere, biogas systems significantly reduce GHG emissions (Sakar et al., 2009).

2. Composting and Vermicomposting
Aerobic composting of organic waste stabilizes biomass and produces nutrient-rich organic manure. Use of microbial inoculants accelerates decomposition and minimizes methane release. Vermicomposting with earthworms improves nutrient cycling, enhances soil fertility, and reduces the carbon footprint of waste disposal.

3. Biochar Production
Through pyrolysis of livestock waste and crop residues, biochar is produced—a stable carbon-rich material. Biochar sequesters carbon in soils for hundreds of years, improves water retention, and reduces nitrous oxide emissions from fertilized soils (Lehmann & Joseph, 2015).

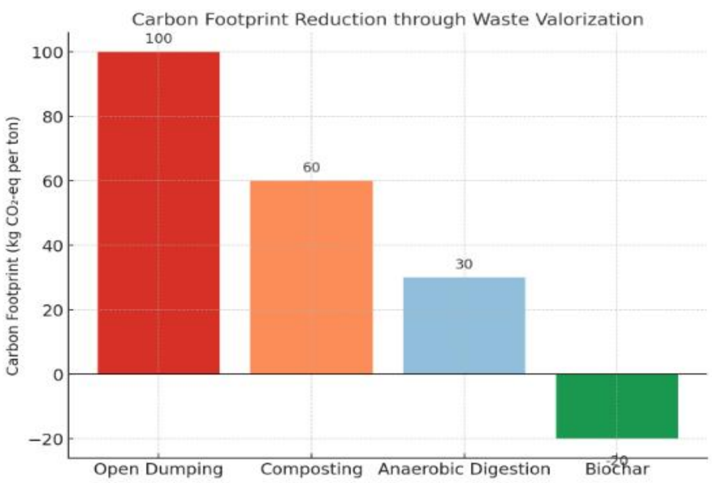
4. Algal Systems for Wastewater Treatment
Effluents from livestock and food industries can be treated with microalgae. The algae assimilate nutrients while producing biomass that can be used for biofuels, animal feed, or biofertilizers. Such systems close the nutrient loop and act as carbon sinks.

5. Circular Economy Approaches
Integration of livestock, crops, and waste-to-energy systems forms circular farming models, where waste from one sector becomes input for another. This reduces reliance on synthetic fertilizers and fossil fuels, ultimately lowering the carbon footprint of farms.

Waste Valorization and Carbon Footprint Reduction
The carbon footprint of livestock production is primarily due to methane (CH_4) and nitrous oxide (N_2O), which have global warming potentials 28 and 265 times higher than CO_2, respectively. Green technologies lower carbon footprints in multiple ways:

- Biogas systems: Prevent methane release by capturing it for energy.
- Composting with microbial inoculants: Reduces uncontrolled emissions compared to open-air decomposition.
- Biochar: Locks carbon in soil for centuries, offsetting emissions.
- Nutrient recycling: Cuts dependence on chemical fertilizers whose production is energy-intensive and CO_2-heavy.

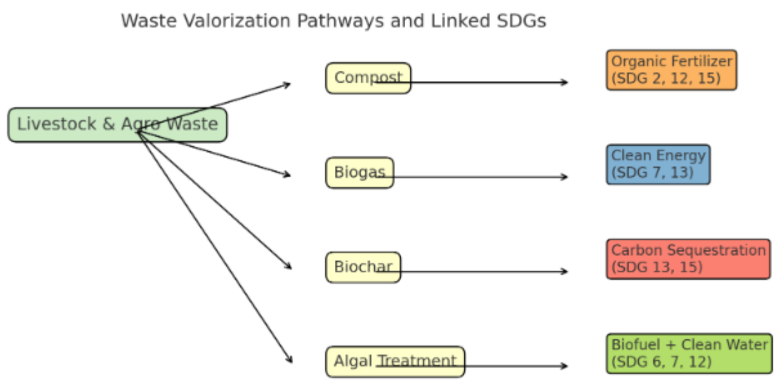
A study by Gerber et al. (2013) estimated that adopting improved manure management technologies can reduce GHG emissions from the livestock sector by up to 30%, significantly shrinking its carbon footprint.



Waste Valorization and the Sustainable Development Goals (SDGs)

Valorization of livestock and agricultural waste directly aligns with several UN SDGs:

- **SDG 2:** Zero Hunger – Organic fertilizers improve soil health, ensuring sustainable food production.
- **SDG 3:** Good Health and Well-being – Proper waste treatment reduces water pollution and zoonotic disease risks.
- **SDG 6:** Clean Water and Sanitation – Wastewater treatment with algae and biofilters prevents contamination of water resources.
- **SDG 7:** Affordable and Clean Energy – Biogas and biofuels provide renewable, decentralized energy solutions for rural areas.
- **SDG 12:** Responsible Consumption and Production – Promotes a circular economy by turning waste into resources.
- **SDG 13:** Climate Action – Waste valorization reduces greenhouse gas emissions and strengthens resilience to climate change.
- **SDG 15:** Life on Land – Sustainable soil management through compost and biochar enhances biodiversity and prevents land degradation.



Challenges and Way Forward

While the benefits are clear, several challenges hinder widespread adoption: high installation costs of biogas and pyrolysis units, lack of technical knowledge, and limited policy support in rural areas. Future strategies should include:

- Government subsidies for green technologies.
- Training programs to build farmer capacity.
- Public–private partnerships for waste-to-energy projects.
- Research into low-cost microbial consortia for efficient waste degradation.

Conclusion

Waste valorization with green technologies is not just a waste management practice, but a climate action strategy. By converting livestock and agricultural waste into bioenergy, fertilizers, and carbon-rich products, we can simultaneously reduce greenhouse gas emissions, lower the carbon footprint, and contribute to multiple Sustainable Development Goals. With strong policy support, scientific innovation, and farmer participation, waste valorization can become a cornerstone of global efforts to mitigate climate change while enhancing agricultural sustainability.

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THE PIVOTAL ROLE OF SUPPLY CHAIN MANAGEMENT IN SAFEGUARDING TRADITIONAL FOOD SYSTEMS

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Abstract
Traditional food systems are more than just ways to acquire food; they are undoubtedly part of cultural heritage, right next to the hotspots of biodiversity and repositories of sustainable agricultural knowledge. Yet it is globalization with its quite destructive arms of industrialization and the ever-changing consumer preferences that pose the gravest threats to the continued existence of traditional food systems. Supply Chain Management (SCM) is one among these potential routes to help safeguard these cherished systems by streamlining operations, enhancing cooperation amongst stakeholders, and promoting sustainability along every dimension. This article looks at the multifaceted role of SCM in guaranteeing traceability from farm to fork, mitigating food wastage, and increasing access to markets for smallholder producer-guardians of these systems. Special mention is made of the peculiar challenges faced, especially in the developing world, such as infrastructure deficits, financial constraints, and convoluted regulatory processes. The spotlight would be cast upon some promising SCM initiatives, cutting-edge digital tracking technologies, cooperative business models empowering producers, and favorable policy frameworks nurturing these systems. The findings would strongly suggest that the combinations of modern SCM practices with traditional food systems would not only increase the competitiveness of these systems but also ensure their cultural authenticity and environmental stewardship.

Keywords: Supply chain management, traditional food systems, sustainability, market access, traceability, food safety

Introduction

Traditionally, food systems are the whole package of practices directly related to food production, processing, and distribution. These practices have evolved naturally over generations. They are based on local knowledge and sustainable utilization of natural resources and have time-honored agricultural techniques. These systems also strongly contribute to their cultural identity, local food security, and biodiversity. However, the pressure of globalization in its various forms, including rapid urbanization and the dominance of industrial food production, affects these systems very adversely. The concern is mainly about authenticity in food, sustainability of production processes, and viability of such systems in the long run.

Supply Chain Management (SCM) is very important in addressing such issues as improving efficiency throughout the supply chain and strengthening collaborative relationships among involved parties at all points of the supply chain, such that SCM has much to do with the sustainability of traditional food systems. It is through optimizing logistical processes, strict product traceability requirements, strong supplier relationships, and solid quality control systems that effective SCM achieves this goal.

Supply chains have a relatively simple definition: short distribution networks close to a particular community; they advocate very specific, tailored SCM strategies if they are to thrive and survive in modern-day competitive and sustainable markets.

This article would consider the multifaceted role of SCM in preserving traditional food systems, elaborating on its profound effects on efficiency, overall sustainability, and crucially, market access. It would also address the major challenges faced by traditional food supply chains and a possible avenue through which to strengthen SCM functionalities within this unique context.

Literature Review

The Indispensable Role of SCM in Traditional Food Systems

Supply Chain Management is concerned with the management of relationships between the various businesses involved in the efficient production and supply of agribusiness products from farm to consumer (Woods, 2004). In Asia, it has recorded significant growth in the agri-food sector, with modern techniques like RFID traceability systems being employed (Noomhorm& Ahmad, 2008). SCM is said to make food industries more competitive and, thus, it could probably add to food security by enhancing food availability, access, and stability of supply (Aji, 2010). The lack of collaboration and small farmers' restricted capacity has and will continue to be the limiting factors in the application of SCM in the traditional food systems. Government support to SCM adoption may come in the form of facilitation and education and policy shifts from production focus to a whole-chain approach (Aji, 2010).

The Significance of Relationship Quality in Traditional Food Supply Chains

Study shows relationship quality (RQ) importance for traditional food supply chains. RQ is composed of factors such as trust, commitment, and satisfaction, which favorably impact the performance of the supply chain (SCP) and innovation ability (Mesić *et al*., 2018; Gellynck *et al*., 2010). Good contacts allow for sharing resources and also accumulate motivation for innovation leading to a competitive edge (Gellynck *et al*., 2010; Lees *et al*., 2020). It is against this background that RQ, within the food supply chain, has a meaningful impact on supplier performance, thus relating the resource-based and relational views of firms (Lees *et al*., 2020). RQ emerges as important in both modern and traditional supply chains, as pointed out by a study of Indonesian chili markets, where the segment of farmers related to their buyers perceived a high extent of RQ (Sahara *et al*., 2011). These aspects help to substantiate the critical journey that RQ has on enhancing efficacious competitiveness in traditional food supply chains.

The Transformative Role of Technology in Traditional Food SCM

The changing face of technology as it relates to traditional food supply chain management (SCM) is a subject of recent literature. Inventory tracking, quality monitoring, and supply chain coordinating will heavily change in efficient management of resources, be it through reduction in wastage or cost, with the use of electronic devices, such as information technology, and those having sustainable technology (Watson *et al*., 2015).

Industry 4.0 tools, such as the IoT, are availing new standards in the food supply industry through tackling quality, safety, and sustainable issues (Abideen *et al*., 2021). Changing processes at the various stages of food supply chains with technologies such as RFID, blockchain, 3D printing, and autonomous vehicles would improve efficiency and sustainability considering perishability characteristics of food (Haji *et al*., 2020). Nevertheless, these are still faced with critical barriers specifying their application scope and objectives (Abideen *et al*., 2021). Notwithstanding the existing challenges, technological integration into food SCM brings considerable promise in connectivity for increased traceability and control in quality as well as personalized consumer experience (Watson *et al*., 2015).

Persistent Challenges in Traditional Food SCM

Traditional food supply chain management (SCM) suffers from various inherent challenges, such as perishability, safeness, and sustainability (Kohli *et al*., 2025). In the local-context of Tanzania, food processors continue to face technical know-how barriers, and infrastructure limitations, lack of capital, and poor research and development facilities (Ruteri, 2009). The food industry struggles with several issues such as all sorts of global happenings, increasing consumer demands, and complexity among suppliers (Sivakumar & Premrajkumar, 2024). In India, security of food is regarded as a major challenge in sustainable food SCM (Sharma *et al*. 2021).

Technological advancement such as block chains, internet of things, artificial intelligence, and big data analytics looks promising solutions to combat these challenges (Kohli *et al*., 2025). Understanding of SCM concepts among processors is still poor, not allowing them to take advantage of SCM strategies (Ruteri, 2009). Modern doctrines advocate the creation of integrated, agility systems that use advanced analytics and real-time data to improve decision-making and enhance collaboration (Sivakumar & Premrajkumar, 2024).

Discussion

The literature shows that SCM is a major factor in preserving and modernizing the traditional food systems. It has increased traceability, improved relationships with stakeholders, and fostered greater market competitiveness (Aji, 2010; Woods, 2004). The level of benefits that smallholder farmers and other actors realize very much depends on the socio-economic context, infrastructural availability, and policy environment. Traceability appears to be one of the most conspicuous benefits. RFID/blockchain/IoT technologies facilitate the real-time tracking of the food product from farm to consumer, conforming to safety requirements for food and thus instilling consumer confidence (Abideen *et al*., 2021; Haji *et al*., 2020). In traditional systems, where relationships with consumers tend to be established on trust and reputation, these tools give a wider market access to projects that had local credibility. The adoption of these technologies by small-scale producers has nonetheless been hampered mostly by financial and technical barriers (Ruteri&Xu, 2009).A frequent variable is that RQ provides an avenue for improving supply chain performance at a low cost and very high impact. Studies have established that RQ, that is, trust, commitment, and satisfaction, positively influences collaboration, innovation, and sustainability (Mesic *et al*., 2018; Lees *et al*., 2020). In situations where legal or contract enforcement is weak, RQ tends to substitute formal governance mechanisms, making informal agreements work (Gyau *et al*., 2011). The remaining obstacles that threaten the robustness of traditional food SCM include such things as perishability, fragmented supply networks, poor storage facilities, and inability to meet an ever-increasing level of safety regulations (Sharma *et al*., 2021; Sivakumar&Premrajkumar, 2024). So too do the recoveries from shock events like pandemics, climatic perturbations, and geopolitical disruptions provide evidence for the fragility of a system so heavily reliant on informal structures (Kohli *et al*., 2025). The described policy alignment is another binding variable with respect to risk and success associated with SCM programs. Government facilitation, subsidies geared toward certain activities, and support cooperatives could alleviate the structural weaknesses and facilitate the adoption of advanced SCM strategies, even by very small producers (Aji, 2010). In the absence of such supportive policy, the integration of technology may remain confined among large capitalized players, further alienating small producers.

Strategic Recommendations

From the review of the literature, numerous strategies for enhancing supply chain management (SCM) in traditional food systems have emerged, stressing local context-oriented adaptations for balance between modernization and conservation of cultural and ecological integrity.

Tiered Technological Integration

Small-scale producers face immense barriers when attempting to adopt so-called "advanced" traceability systems, including blockchain or IoT monitoring. We support a tiered integration model starting with inexpensive and low-access digital tools, including mobile market platforms and basic barcode labeling, and moving to more advanced technical solutions (Abideen *et al*., 2021; Ruteri & Xu, 2009). This staged approach will enable greater uptake so that technology becomes an enabler rather than a disrupter of existing ways of doing things.

Cooperative and Cluster-Based Models

Producer cooperatives and regional clusters enhance bargaining power, reduce transaction costs, and facilitate investments in common infrastructure such as cold storage, and processing facilities. Such collective arrangements also create opportunities for joint branding of traditional food products, thereby increasing market visibility and consumer recognition (Mesic *et al*., 2018; Woods, 2004).

Policy Support and Incentive Structures

The government and institutional policies should move away from the production-centered view toward a chain-orientated view. This should include direct subsidies for sustainable SCM practices, put in place friendly regulations that encourage smallholders, and provide incentives for environmentally responsible logistics (Aji, 2010; Sharma *et al*., 2021). Such policies are capable of addressing the structural setbacks faced by small-scale actors in competitive markets.

Capacity Building and Knowledge Transfer

Periodic training programs in logistics optimization, quality assurance, and market intelligence can be organized. The cooperation of universities, NGOs, and agritech companies can be utilized to deliver practical application knowledge in a local context (Gyau *et al*., 2011; Lees *et al*., 2020). This knowledge transfer is vital for putting producers into a position to make informed decisions regarding SCM.

Embedding Resilience and Sustainability

Resilience must be embedded as a design consideration, as traditional food systems are vulnerable to climate change and the disruption of global supply systems. Climate-smart practices—diverse cropping, renewable energy storage, and water-efficient irrigation—should all be embedded in SCM frameworks for longer-term sustainability and cultural integrity (Kohli *et al*., 2025; Sivakumar & Premrajkumar, 2024).

Conclusion

Food systems have constituted cultural heritage and biodiversity conservation with a wealth of sustainable agriculture wisdom, but today under the onslaught of globalization and industrialization, new consumers seem to subject them to some unfathomable demands. Supply Chain Management represents a plethora of options in ameliorating these challenges that include efficiency, creating strong relationships between stakeholders, traceability, and new market access routes. However, modernization of traditional food systems needs to be careful and sensitive. High-cost technologies that are not adequately complemented with capacity-building could lock small actors out of the system. Similarly, socio-cultural contexts ignored in modernization initiatives can inadvertently undermine the very conservation efforts that they seek to uphold. Thus, if a balance comprising tiered technological integration for cooperatives, this would create supportive policy environments together with a practice for sustainability. Modernization would thus be most in tandem with supporting traditional food systems. Through embedded resilience in SCM frameworks, destination stakeholders would keep these systems as economic assets, and even more so, cultural and ecological.

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SUSTAINABLE AQUACULTURE THROUGH INTEGRATED MULTI-TROPHIC SYSTEMS

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Introduction

Integrated Multi-Trophic Aquaculture (IMTA) is an advanced and sustainable aquaculture approach that cultivates multiple aquatic species from different trophic levels within a single system. The goal of IMTA is to create a balanced ecosystem where the waste and by-products from one species, such as uneaten feed and metabolic excretions, serve as valuable inputs for other species, providing nutrients for seaweed or food for filter-feeding shellfish (Choudhary *et al*., 2025). This approach minimizes waste and promotes a healthy aquatic environment.This intentional design, which distinguishes IMTA from simple polyculture, ensures that each species plays a complementary ecological role: fed species like fish or shrimp, organic extractive species such as shellfish, and inorganic extractive species like seaweed (Bohare *et al*., 2025). By mimicking natural ecosystems and food webs, IMTA enhances resource efficiency, improves water quality, promotes biodiversity, and allows for multiple harvestable products, all while reducing environmental impacts. Developed since the 1970s, modern IMTA emphasizes scalability, adaptability, and diversified production, making it an eco-friendly strategy that supports sustainable food production, economic resilience, and ecosystem health critical considerations as global food demand rises and environmental challenges intensify (Khanjani *et al*., 2025).

Principles of IMTA

IMTA operates on the principle of nutrient recycling and ecological balance, where high-trophic-level species like finfish produce waste that serves as food or nutrients for lower-trophic-level species such as shellfish and seaweed. This creates a synergistic ecosystem that reduces waste discharge, improves water quality, and enhances overall system efficiency. IMTA integrates aquatic species from different trophic levels (Fig. 1), transforming potential pollutants into valuable resources, while filter feeders and macroalgae extract and convert nutrients to limit eutrophication. By facilitating nutrient flow between species, the system promotes natural bioremediation, biodiversity, and ecosystem health. Carefully selected and proportioned species not only complement each other ecologically but also provide multiple commercial products, diversifying income streams and improving economic resilience. Scalable, adaptable, and guided by best management practices, IMTA supports sustainable, profitable, and socially accepted aquaculture.

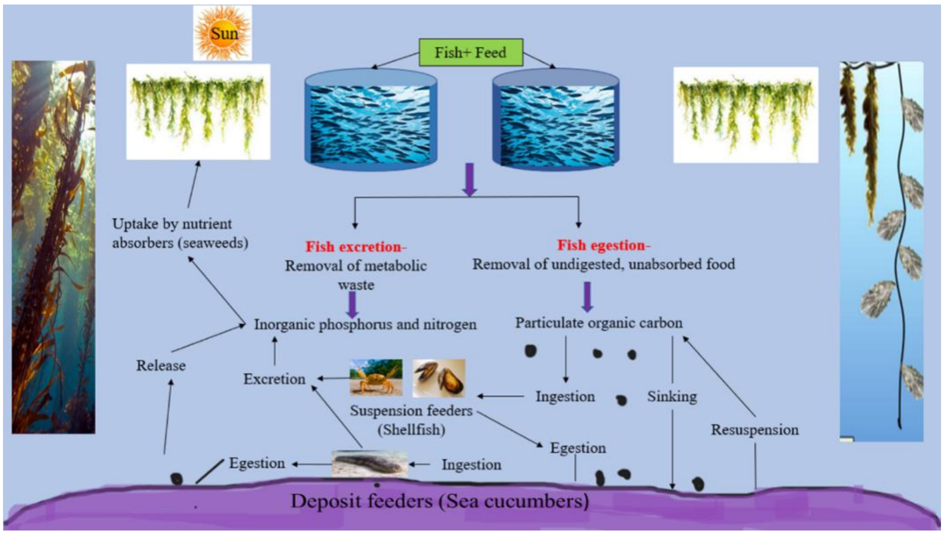

Fig. 1 Schematic representation of an integrated multi-trophic aquaculture (IMTA) system

Components of IMTA Systems

IMTA systems comprise multiple components that function together to maintain a balanced ecosystem. Key components include species selection and trophic levels, system design and configuration, and water quality management and monitoring.

Species Selection and Trophic Levels: Species selection is a crucial aspect of IMTA systems, as it determines the balance and efficiency of the ecosystem. Species are chosen based on their trophic levels, with each occupying a specific position in the food chain. The main trophic levels in IMTA systems include (Fig. 2):

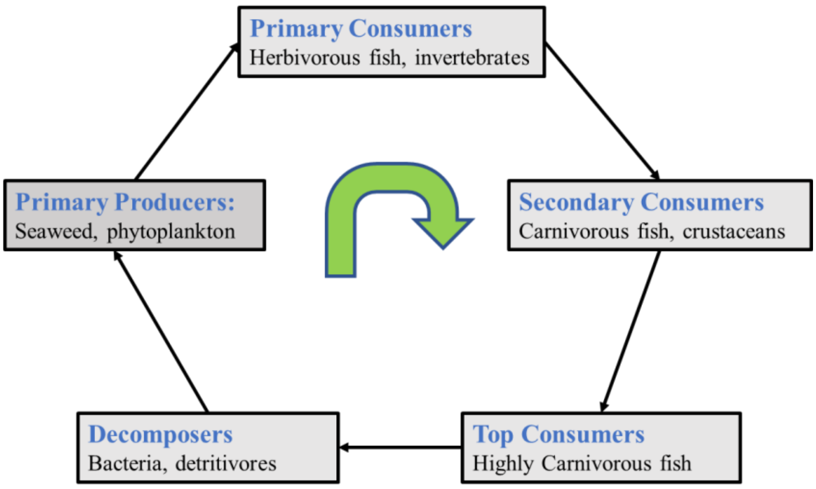

Fig. 2 Illustrates the different trophic levels in an IMTA system

Design and Configuration of IMTA Systems*:* The design and configuration of IMTA systems depend on the specific goals and context of the operation. Typically, these systems include cultivation units for different species, water treatment and management systems to maintain optimal water quality, and monitoring and control systems to track environmental parameters and overall system performance. Together, these components work in harmony to support a balanced ecosystem, ensuring efficient nutrient cycling and healthy growth of all species within the system.

Table 1. Presents an example of how species and trophic levels can be arranged in an IMTA system

Component	Species	Trophic Level	Role in IMTA System
Seaweed cultivation	Seaweed	Primary producer	Absorbs nutrients such as nitrogen and phosphorus from water, reduces eutrophication.
Fish farm	Herbivorous fish	Primary consumer	Consumes feed and converts it into biomass; produces waste that serves as nutrients for other species.
Shrimp farm	Carnivorous shrimp	Secondary consumer	Feeds on smaller organisms or formulated feed; contributes organic matter and waste.
Bivalve farm	Mussels	Primary consumer	Filter-feeds on plankton and suspended particles; improves water clarity and quality.
Detritus farm	Sea cucumbers	Decomposer	Consumes detritus and organic waste; recycles nutrients back into the system

Water Quality Management and Monitoring: Water quality management and monitoring are essential in IMTA systems to ensure optimal conditions for all species. This is achieved through strategies such as water exchange and circulation, removal and treatment of waste, and continuous monitoring of key water quality parameters, including pH, temperature, and nutrient levels. Together, these measures help maintain a healthy and balanced aquatic environment, supporting the growth and productivity of all cultured species.

Types of IMTA Systems

IMTA can be implemented in various environments:

Marine IMTA systems: Combining finfish cages with filter-feeding shellfish (mussels, oysters) and seaweeds to utilize dissolved and particulate nutrients.

Freshwater IMTA systems: Combining freshwater fish with aquatic plants, molluscs, and detritivores to recycle organic matter efficiently.

Land-based vs. sea-based systems: Land-based IMTA uses controlled tanks or ponds, while sea-based IMTA relies on cages and longline seaweed cultivation. Both aim to optimize nutrient recovery and productivity.

Environmental and Economic Benefits

IMTA provides multiple benefits across environmental, economic, and sustainability dimensions. Environmentally, it reduces nutrient discharge into surrounding waters, improves water quality, and helps mitigate eutrophication. Economically, it increases total biomass production, diversifies income sources, and enhances resilience against market fluctuations. From a sustainability perspective, IMTA promotes circular economy principles, making aquaculture more ecologically responsible and socially acceptable (Chopin *et al.*, 2016).

Challenges and Limitations

Despite its advantages, IMTA faces several challenges. Technically and operationally, it requires careful management, knowledge of species compatibility, and significant infrastructure investment. Market and economic barriers may arise, as some IMTA products lack market recognition or sufficient value. Additionally, the complexity of these systems can increase the risk of disease and pathogen transfer if biosecurity measures are not properly implemented.

Case Studies and Global Examples

Several successful IMTA implementations worldwide demonstrate its environmental and economic benefits. In Canada's Bay of Fundy, salmon cages are integrated with mussels and kelp, reducing nitrogen load in surrounding waters. In China, freshwater IMTA systems combine carp, shrimp, and aquatic plants, enhancing yield while mitigating pond eutrophication. In Europe, sea-based IMTA in Norway integrates salmon farming with seaweed cultivation, promoting both environmental sustainability and economic resilience.

Future Prospects and Research Directions

IMTA represents a promising frontier for sustainable aquaculture, with several avenues for future development. These include genetic and selective breeding to enhance species compatibility, the use of smart monitoring technologies such as IoT and AI for system optimization, and policy incentives or subsidies to encourage wider adoption. Additionally, IMTA has the potential to improve climate resilience by fostering more robust and efficient aquatic production systems.

Conclusion

Integrated Multi-Trophic Aquaculture (IMTA) offers a sustainable and ecologically responsible approach to aquaculture by cultivating multiple species from different trophic levels in a single system. By recycling nutrients and reducing waste, IMTA improves water quality, enhances biodiversity, and promotes ecosystem balance. Economically, it diversifies production and increases resilience, while environmentally, it mitigates nutrient pollution and supports sustainability. With advances in system design, species selection, and smart monitoring, IMTA has the potential to address growing seafood demand, support food security, and foster climate-resilient aquaculture, making it a key strategy for the future of sustainable aquatic production.

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STARCH-BASED COATINGS FOR THE POSTHARVEST PRESERVATION OF FRUITS AND VEGETABLES

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Abstract
Effective and affordable postharvest preservation of fruits and vegetables remains a major challenge in the food industry. Starch-based coatings offer promise due to their abundance, biodegradability, and safety but are limited by weak mechanical strength and high water absorption. To address these issues, starch is often combined with other materials to form composites. This study reviews the principles, functional properties, guidelines, and recent advances in starch-based edible coatings, aiming to improve their role in extending the shelf life of fruits and vegetables.

Introduction

Fruits and vegetables give people vital nutrients and are crucial for preserving human health and averting the development of many illnesses (Mostafidi, Sanjabi, Shirkhan, & Zahedi, 2020). Fresh produce has high metabolic activity and a high water content, typically between 75% and 95%. They are therefore vulnerable to quality deterioration and decay, which has emerged as a possible cause of foodborne illnesses, and are readily contaminated by harmful microbes such bacteria, fungus, and viruses during postharvest storage and transit (Ahmed *et al*., 2022). According to reports, the average annual loss of fruits and vegetables in developing Asia is around 50% (Acedo, 2019). Between 30 and 50 percent of fruits and vegetables are lost after harvest in sub-Saharan Africa (Makule, Dimoso, &Tassou, 2022). One of the most pressing issues in the food industry has always been lowering postharvest losses of fruits and vegetables. This has led to the development of a number of fruit and vegetable preservation technologies, such as chemical preservation (H. Zhang, Liu, Wang, Yang, & Li, 2023), refrigeration (Hernandez-Ramos, García Mateos, Castillo-Gonz´ alez, & Ybarra-Mocada, 2023), modified atmosphere (Dogan & Erkan, 2023), and irradiation (Haider *et al*., 2023).

Preservation principles of starch-based coatings

Fruits and vegetables are frequently preserved via surface coating, and the preservation principle has various facets that fall into two categories: intrinsic qualities and functional features. All edible coatings have inherent qualities, however functional qualities can be added by adding the right functional materials based on certain requirements.

Inherent properties

a) Isolation and protection :Edible coatings form a barrier that limits contact between produce surfaces and external contaminants such as dust and microbes, helping preserve nutritional value and structure (Y. Du *et al*., 2021). Their mechanical strength also buffers produce against damage during storage and transport. For example, Khorram *et al*., replaced natural wax lost during handling with shellac, which dries quickly, is odorless and non-stick, and gives fruits a high gloss (Khorram, Ramezanian, & Hosseini, 2017).

b) Inhibition of water evaporation: Fruits and vegetables lose water during storage, transit, and handling due to respiration and environmental factors like temperature and humidity, leading to quality decline, wilting, and peel shrinkage. Once moisture content drops to 3–10%, they wither irreversibly and lose marketability (Hoffmann, Ronzoni, Silva, Bertoli, & Souza, 2021; Harker *et al*., 2019). Edible coatings help slow water loss, reduce transpiration, and limit moisture movement through the skin, thereby preserving quality.
c) Gas exchange inhibition: Fruits and vegetables exchange CO_2, O_2, and ethylene during respiration and ripening (Kim, Choi, Kim, & Moon, 2022; Soares *et al*., 2023). Edible coatings reduce the partial pressure difference between internal and external gases, creating a low-O_2, high-CO_2 environment that slows respiration, reduces transpiration, and delays ripening (Q. Zhang *et al*., 2023; X. Zhang, Zhang, Liu, Du, & Tian, 2019). When O_2 drops below 8%, ethylene synthesis declines, extending quality retention (Kader, Zagory, & Kerbel, 1989). However, coating selection should consider respiration rate, transpiration, and storage conditions, as altered gas permeability may cause anaerobic respiration (Kowalczyk *et al*., 2019).

Progress in starch-based coatings

a. Starch coatings

The choice of film-forming matrix material greatly influences the performance of edible coatings for fruits and vegetables. Commonly studied matrices include cellulose derivatives (Pan Ahirad, Nagshiband Hassani, Ghanbarzadeh, Zaare-Nahandi, & Mahna, 2019), starch (Xie *et al*., 2018), polylactic acid (Dawin, Ahmadi, & Taromi, 2019), chitosan (Deng, Jung, Simonsen, & Zhao, 2018), and proteins (Azevedo *et al*., 2018). Among these, starch has gained prominence due to its abundance, renewability, biodegradability, biocompatibility, low cost, good film-forming ability, and non-greasy finish (Dai, Zhang, & Cheng, 2019b; Xie *et al*., 2018).

Raw starch coating

Extensive research has explored starch coatings for fruit and vegetable preservation, spanning various produce types and starch sources. In recent years, studies on raw starch coatings have yielded promising results. For example, Nawab, Alam, and Hasnain (2017) evaluated mango kernel starch coating to extend the shelf life of tomatoes at room temperature. Compared with uncoated tomatoes, coated fruits exhibited delayed ripening, reduced weight loss, and smaller changes in soluble solids, titratable acidity, ascorbic acid content, firmness, and rot rate. This treatment was effective in preserving quality for up to 20 days at room temperature. Similarly, Medina-Jaramillo *et al*. investigated potato starch coatings on Andean blueberries and found that the coating significantly reduced the fruit's gas exchange rate during 12 days of storage. By the end of the period, the respiration rate of coated blueberries was approximately 27% lower than that of untreated fruit.

Modified starch coating

Starch can be modified in various ways to improve its application performance. Punia *et al*. (2019) found that wheat starch modified with octenylsuccinic anhydride had higher peak and final viscosities than native starch and, when used as a grape coating, helped preserve total phenolic content and carotenoids, extending shelf life to 13 days. Thongmeepech, Koda, and Nishioka (2023) used thermomechanical modification of tapioca starch, reducing crystallinity without chemical reactions and enhancing mechanical properties of thermoplastic starch films. Similarly, Kaur, Sandhu, Bangar, and Whiteside (2022) reported that OSA-modified starch showed increased swelling capacity (12.96 to 21.72) but reduced amylose content and solubility, and coatings reduced plum weight loss from 8.09% (natural starch) to 5.42%.

Table 1: Advances in the application of starch coatings.

Object	Formulation	Category	Reference
Tomato	4 % mango kernel starch, 1 % glycerol and 1 % sorbitol	Raw starch coating	Nawab *et al*., (2017)
Andean blueberry	2 % potato starch and 0.6 % glycerol	Raw starch coating	(Medina-Jaramillo *et al*., 2019)
Strawberry	6 % seed starch and12% glycerol/sorbitol	Raw starch coating	(Costa *et al*., 2023)
Plum	The ratio of octenyl succinic anhydride (OSA) modified rye starch: glycerol = 2:1	Modified starch coating	(Kaur *et al*., 2022)
Fres-cut apple	4 % phosphorylated oxidized (PO) starch and 33 % glycerol	Modified starch coating	(Y. Li *et al*., 2023)
Strawberry	Cassava starch chemically modified with amphiphilic maleic anhydride-poly (ethylene glycol) methyl ether (StC-g-(Ma-mPEG)) without plasticizer	Modified starch coating	(M´ endez, M´ endez, Martínez, Vargas, &L´opez, 2022)

Conclusion

Here's the shortened version without losing the core meaning:

Starch offers wide availability, low cost, and good biocompatibility, making it promising for fruit and vegetable coating preservation. To address its poor mechanical strength and high water absorption, strategies like material blending, nano-enhancement, and active molecule addition have been developed, yielding coatings with improved properties and effective postharvest preservation. Self-reinforced nanocomposite coatings, with strong structural compatibility, further enhance physicochemical performance. Future resHere's the shortened version without losing the core meaning:

Starch offers wide availability, low cost, and good biocompatibility, making it promising for fruit and vegetable coating preservation. To address its poor mechanical strength and high water absorption, strategies like material blending, nano-enhancement, and active molecule addition have been developed, yielding coatings with improved properties and effective postharvest preservation. Self-reinforced nanocomposite coatings, with strong structural compatibility, further enhance physicochemical performance. Future research should focus on coating–produce interface interactions, mechanical stress effects during transport, food safety assessments, and molecular preservation mechanisms. Research should focus on coating–produce interface interactions, mechanical stress effects during transport, food safety assessments, and molecular preservation mechanisms.

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FARMERS INNOVATIVE FARMING TECHNIQUE FOR BREEDING AND REARING OF *H. fossilis* (Singhi) REVOLUTIONIZING AQUACULTURE PRACTICE IN WEST BENGAL, INDIA

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Introduction

Singhi (*Heteropneustes fossilis*)also known as Asian stinging catfish is an air breathing catfish which is endemic to south east Asian country like India, Bangladesh, Myanmar, Thailand, SriLanka. In nature it is found in swampy,marshes and muddy rivers. It is one of the important commercial fish in India due to its nutritional profile. Its ability to survive in low oxygen water make it excellent choice for the farmers for its aquaculture. Despite its potential in aquaculture, singhi have not reached to every farmer, due to seed unavailability.The fish is very much popular in West Bengal and other easter part of our country. Many hatcheries have been setup in west Bengal for supply of singhi seeds. But breeding of singhi in controlled environment is a challenging task.

A young and innovative farmer Imran Ali Mollah ofUlubariahave done successful breeding and culture of singhi in cement tank and tarpaulin based circular tanks. Unlike traditional methods he developed his own innovative methodsof breeding and culture of singhi which turned his small farm into thriving business. Instead of earthen ponds, tarpaulin based circular tanks were used for better water circulation, waste removal and controlled condition to recycle water as needed. For breeding rectangular cement tanks were usedwherein breeding as well as larval rearing takes place subsequently. This article will highlight some of the activities and innovativeness he has put to come out as a successful singhi breeder.

Fig. 1 Farm of Imran Ali Mollah at Ulubaria, Howrah district, West Bengal

Innovative technique for breeding and culture of Singhi

Circular tank system

This circular tank is made of tarpaulin sheet which have a capacity of 10000 lit with a diameter of 12 feetand height of 4 feet. The bottom of the tank has slope towards the middle of the tank where outlet is provided with valve to control the flow of water. It helps in removing of uneaten feed and debris accumulated during the culture period. This circular tank is used as rearing unit as well as broodstock tank.

Fig.2 Tarpaulin based circular tank 10000 lit capacity

Rectangular cement tank

The breeding unit cum larval rearing unit is a rectangular tank made of cement. The dimension of the four tank is (4 x 4 x 1) feet and another four tank (5 x 5 x 1) feet. Total there are 8 numbers of rectangular tanks. Each tank is used as breeding pool during the breeding season and later the same tank is used for larval rearing as well as maintaining the broodstock. These rectangular tanks are used for live feed culture like zooplankton and tubifex also.

Fig.3 Rectangular cement tank for breeding and larval rearing

Low-cost automatic feeder

A low-cost automated feeder is kept in each tank for feeding in a given schedule. The feeder is made of 10 lit plastic bottles for storage of feed. At the bottom of the bottle an outlet for dispersing the feed is attached made of 0.5-inchPVC pipe. A lid is designed at the opening of the pipe via solenoid valve. As the valve is magnetic, even if power failure is there during dispersing the feed the valve closes automatically. This will prevent dispersing of excess feed during power failure. The valve is controlled by a timer which can be preset as required.

Fig. 4 Low cost automated feeding machine with timer

Tubifex culture unit

In the farm tubifex is cultured for feeding the larvae of singhi. Artificial feed is not recommended at the initial phase of larval rearing. The feed is not acceptable to the young larvae and thus pollute the water. Tubifex worm inoculum is collected from nearby drain and kept in the rectangular tank with soil base with slight flow of water. Organic matter source like decay vegetables is provided. Tubifex is washed in clear water and then chopped into smaller pieces. These chopped tubifex is fed to the larvae for 10 days. The singhi larvae at the initial stage is carnivorous in nature and prey upon live feed like tubifex, zooplankton etc.

Mixed Zooplankton culture

The circular tarpaulin tanks are used for production of mixed plankton like Moina, daphnia, infusoria etc. which is given as feed to the singhi larvae. Around 5000-6000 lit of water is maintained in the circular tank with aeration. Nutrient supplement like cow dung, organic matter like chicken waste etc. are provided for proper growth of the plankton. Phase manuring with SSP, urea is done to maintain the plankton concentration.

Fig.5 Circular tank for Zooplankton production

Broodstock management of Singhi fish

The brooders are maintained in the circular tank. Commercial floating feed containing 35-40 % protein was fed to the brooders along with the natural planktons. About 10% of water was exchanged regularly by siphoning from the bottom of the tank. Water from the plankton culture tank is used to fill the brooder tank along with freshwater. Feed is given 5-8% body weight at regular interval, at least once in every hour. The timer of the automated feeder is set in such a manner that it supplies feed for 6-10 sec every hour. These feeding schedule can be changed depending of biomass of the brooders in the tank.

Water quality management

Regular exchange of water takes place. The optimum water quality parameters like DO are maintained @ 3-5 ppm, pH- @ 7.5-8.5. Ammonia and nitrite level is kept at the minimum level by exchange of water. Water temperature is optimal ranging from 24-30 degree Celsius. During winter season feeding is decreased to avoid any infection.

Singhi breeding operation

During the onset of monsoon in the month of July-Aug breeding operation will commence. The maximum larvae produced per breeding cycle is 10 lakhs. Male and female brooder are brought from the broodstock tank and acclimatized in the cemented tank. Inducing hormone like ovasis, spawn pro etc. which are GnRHs based inducing agents are used for breeding of singhi. The male female ratio is kept @ 2:1 since females are bigger in size. The average weight of the brooders is about 50-60 grams. In each rectangular tank 2 kg of male and female were used for breeding purpose. Mass breeding is done where many brooders are kept together in the breeding tank. The dose of inducing agent used is 1 ml/kg and 0.5 ml/kg body weight for female and male respectively. Based on the condition of brooder female is injected up to 2 ml/kg body weight. If the genital opening of the female brooders is reddish in colour then the condition is said to be best. If the colour fades and become whitish then it is considered to be a bad brooder. If the male broodersare in plenty then 1:1 ratio of male to female brooders can be used for breeding operation.

Usually, intramuscular injection is given to the brooder in the evening hours. The latency period is around 6-8 hours and spawning takes place early morning. The water depth in the breeding tank is kept 1 foot with light shower from the top. Water level is lower to half feet and spent brooders are removed. The brooders that have not spawned are injected with inducing agent @ 0.1-0.5 ml/kg body weight and checked for any possible breeding. Once breeding is over the spent brooders move to the side of the tank. The brooders are removed using brooder collection net. The eggs remained in the tank and kept for incubation. The hatching period is about 16-20 hours depending on the water temperature. Any unfertilized eggs are removed by siphoning with small pipes. After the hatching is over the larvae starts movement. Proper hide outs are provided during this time.

Fig.6 Breeding tank of Singhi

Larval rearing

Larval rearing is done in the rectangular cemented tank. The water depth is maintained up to 30 cm. Regular exchange of water up to 50% depending on the quality is done. Hiding space for larvae are provided which is made up of broken agricultural pipes and flower pot. Larvae are fed with chopped tubifex and mixed zooplankton. Any uneaten feed is removed to avoid bacterial growth.

Health management

As such there is no major infection reported in Imran's farm. But during handling of stock pectoral spine may injure each other. This can lead to bacterial and fungal infection. Even fish are prone to infection during winter season and disease may occur. As preventive measure fungicide and other agents like copper sulphate are used during rare infection.

Fig. 7 Fungicide and Copper sulphate

Conclusion

Imran's way of breeding and culture of singhi fishis a mix of traditional farming combined with scientific innovation which have revolutionize farming. The success he made is not just a personal triump but a beacon of hope for aspiring fish farmers across West Bengal and our country at large. Farmer like him will be required all across the country for bringing change in the fisheries sector and ultimately increase the fish production.

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SERIOUS SIGNIFICANT REASONS BEHIND CHANGES IN *Tenualo sailisha* MIGRATIONS FROM ANDHRA PRADESH ESTUARIES

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Tenualo sailisha (Hamilton-Buchanan, 1822) is one of the significant anadromous fish species and very popular fish species especially in Bay of Bengal (BoB) and in South Asia and some of the middle eastern countries due to its exceptional and delightful taste and high nutritious value. Meanwhile, it's having cultural and ecological significance being one of the common food sources shared across the nations (Ahmed *et al.,* 2021). Several scientific studies proved that it is a rich source of amino acids and vital fatty acids that can help reduce the risk of cardiovascular disease, lower cholesterol levels, and sustenance brain development (Alam and Naser 2020). The status of hilsa shad in this province has driven a large number of scientific studies and these studies identified the knowledge gaps and mitigated for future research directions. Hilsa has varied distribution in the marine, freshwater and estuarine environments of India. Marine distribution ranges are mainly West coast of India in the Arabian Sea and the Bay of Bengal of East coast (Pillay and Rosa 1963).

At present it is one of the most expensive and commercially demanded fish, which is declining rapidly in past five years approximately, especially in Andhra Pradesh estuarine regions. To examine the ground level truth, we conducted an interactive survey with fisherfolks of the region from starting of June to Mid of the August and the results indicated reasons behind the decreased population of *Tenulo shailisha.* Management of sustainability of hilsa fish in the Bay of Bengal on emergency call and need to initiate immediate implementations of scientific and proper management techniques to conserve the species. Collaborating though artisanal fisherfolks and local fishermen communities is the most important task should be on roll within immediate action plan.

Tenulo shailisha Anadromous fish

- As per scientific reports this species travels 11 thousand nautical miles to breed, particularly to estuaries and river mouths.
- Godavari River mouth is one the most well-known region for the breeding grounds for this species.

Present scenario of estuaries of Andhra Pradesh

- In Andhra Pradesh availability of *Tenulo shailisha*is limited to flood season only, when the river water turns to red colour is a sign of anadromous migration of *Tenulo shailisha.*
- *Tenulo shailisha* locally called*Vilasa (Marine waters*), when it reaches riverine or estuary it calls as*Pulasa (Fresh waters).*
- *Tenulosha Ilisha*highly available in estuarine waters from June to October, but the peak season is July to September, remaining depends on the floods.
- We surveyed large scale fish sampling stations of Yanam, BhairavaPalem, Kotipally, Yeddurlanka, Ravulapalem, and Siddhantham, where fishermen's conduct fishing activity whole night to capture the highly commercial fish species.

- ❖ Unfortunately, our team observed only 15 number of captured fish species in entire two and half month survey.
- ❖ Earlier one kilogram fish rate at fishermen was 10-15 thousand rupees, and usually get each 4–5kilogram fish species. If one fisherman gets 5-6 fish species of 4–5-kilogram fish species means it's a huge amount to them in this peak season.
- ❖ Yearly, particularly from Godavari estuary region captures nearly 40 MT (Metric Tonnes) *Hilsa* fish, but this year as per fishermen insights not even 10% of the total catch was captured.
- ❖ At present drastic conditions of fish unavailability, the fish species rate was hiked to 25-26 thousand for kilogram, that too some people booking fish species at fisherman level giving 5-10 thousand advances to them, this condition clearly indicating the high demand of this species.

Major reasons behind the drastic conditions

- ❖ Krishna-Godavari (KG basin) offshore dredging activities creating lot of disturbance to the fish species through sound pollution.
- ❖ Reliance, ONGC and other oil companies regular dredging disturbing waters through substantially improved and unavoidable water vibrations because of sound pollution which having major impact on this species particularly in their peak breeding seasons.
- ❖ Mainly at Yanam, Bhairavapalem, Gadimoga, Antharvedi, and Karawaka areas are completely industrialized were chemical residues, Aqua residues directly draining into the waters.
- ❖ Sulphur, Ammonia, Lead and Mercury are the major leading chemicals responsible for drastically impacting fish population and its breeding activities including their health, not limited to the particular fish species but all aquatic organisms.
- ❖ All above activities are influencing the migration of *Tenulo shailisha* towards Odisha and West Bengal coasts.

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Fig: 1 : Grading of Hilsa fish

Fig: 2 Fisherman happiness and keen observation after getting the fish

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SELF-HELP GROUPS (SHGS): AN INSTRUMENT FOR SOCIAL AND ECONOMIC EMPOWERMENT

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Introduction

Self-Help Groups (SHGs) are voluntary associations of people, typically from similar socio-economic backgrounds, who come together to save small amounts of money regularly, create a common fund, and provide loans to each other at reasonable interest rates. They play a vital role in empowering rural communities, especially women, by promoting savings, entrepreneurship, and social cohesion. SHGs have emerged as an important tool for poverty alleviation, women empowerment, and inclusive development in India and other developing countries.

Importance of SHGs

i. **Financial Inclusion:** SHGs provide access to credit and savings opportunities to marginalized groups who are often excluded from formal banking systems.
ii. **Women Empowerment:** Women-led SHGs enhance decision-making power, self-confidence, and leadership roles in families and communities (NABARD, 2017).
iii. **Poverty Reduction:** SHGs help in improving household income and reducing dependence on moneylenders.
iv. **Social Development:** SHGs address issues such as health, education, sanitation, and domestic violence by fostering collective awareness.
v. ***Skill Development:*** Members often undergo training in entrepreneurship, financial literacy, and vocational skills.

Formation and working of SHGs

- **Size:** Typically consists of 10–20 members.
- **Savings and Credit:** Members save small amounts regularly, which are pooled into a group fund. This fund is used to provide collateral-free loans to members.
- **Linkage with Banks:** Under the SHG-Bank Linkage Programme (SBLP) initiated by NABARD in 1992, SHGs can avail institutional credit after demonstrating financial discipline.
- **Decision Making:** Decisions are taken democratically, often by women leaders elected within the group.

Advantages of SHGs

- **Economic Security**: Increases household savings and investment.
- **Reduced Exploitation:** Lowers dependence on moneylenders.
- **Social Empowerment:** Enhances unity, cooperation, and social solidarity.
- **Entrepreneurship Development:** Encourages micro-enterprises like dairy farming, handicrafts, food processing, and tailoring.
- **Access to Government Schemes:** SHGs serve as channels for implementing rural development schemes such as NRLM (National Rural Livelihoods Mission).

Limitations of SHGs

- **Limited Resources:** The savings capacity of members is often low.
- **Training Needs:** Many SHGs lack adequate financial and entrepreneurial skills.
- Dependence on NGOs/Facilitators: Sustainability becomes difficult without external support.
- **Internal Conflicts:** Mismanagement, irregular meetings, or lack of transparency can weaken group cohesion.

Government Support and Policies

The Government of India and various state governments promote SHGs through different schemes:

- **National Rural Livelihoods Mission (NRLM):** Aims at universalizing SHGs and strengthening them with training, financial support, and credit linkage (MoRD, 2011).
- **NABARD Initiatives:** SHG-Bank Linkage Programme connects millions of SHGs with banks.
- **State Initiatives:** For example, Kudumbashree in Kerala and Mission Shakti in Odisha are successful models of women-led SHG empowerment.

1. **Case Studies**
   - Kudumbashree (Kerala): A women-oriented SHG network that has successfully promoted microenterprises and poverty alleviation.
   - Mission Shakti (Odisha): Over 7 million women are organized into SHGs, playing an active role in social and economic development.

Government of Odisha & Self-Help Groups: Mission Shakti and Beyond

Mission Shakti: A Flagship Initiative for Women's Empowerment

The Government of Odisha launched Mission Shakti on March 8, 2001 (International Women's Day) as its flagship programme to promote women's socio-economic empowerment through the formation and support of Women Self-Help Groups (WSHGs) (Mission Shakti, n.d.-a). Since its inception, Mission Shakti has mobilized around 6 lakh SHGs, comprising nearly 70 lakh women across both rural and urban areas of the state (Mission Shakti, n.d.-a; Ommcom News, 2023).

Mission Shakti has also evolved institutionally—from a programme to a dedicated Directorate, and eventually into a separate Department under the Odisha Government—ensuring better governance, integration, and resource allocation across municipal and block levels (The New Indian Express, 2022; Mission Shakti, n.d.-a).

Financial Support: Interest-Free Loans

To enhance financial inclusion, the Odisha Government introduced subsidized loans for SHGs in 2013 at 2% interest for amounts up to ₹3 lakh. This was later reduced, and by 2019, the government began offering interest-free loans (Mission Shakti Loan) for prompt repayment up to ₹3 lakh for both rural and urban SHGs (Mission Shakti, n.d.-b).

The credit flow to SHGs has significantly expanded—rising beyond ₹11,000 crore in 2022–23, with the average loan size increasing from ₹1.06 lakh in 2016–17 to ₹3.01 lakh in 2022–23 (Ommcom News, 2023). To further strengthen institutional capacity, Block-Level Federations (BLFs) were granted revolving funds of ₹25 lakh each, along with ₹1.5 lakh for administrative expenses, enabling them to support internal lending and capacity-building (MSBLIS, n.d.).

Linkages & Livelihoods: Engaging SHGs Beyond Finance

The Odisha Government has gone beyond credit support by integrating SHGs into service delivery and livelihood programmes. In 2019, the State Cabinet approved outsourcing of services like uniform stitching, electricity meter reading, and mid-day meal operations to SHGs, creating a projected business volume of over ₹1,000 crore annually (The Hindu, 2019; MSBLIS, n.d.).

Sector-specific livelihood opportunities have also been promoted:

- **Pisciculture:** SHGs were granted long-term leases of Gram Panchayat tanks for fish farming, generating harvests worth nearly ₹83 crore from over 4,000 tanks (Orissa Diary, 2023).
- **Paddy Procurement:** SHGs participate in procurement operations, earning more than ₹58 crore in commission cumulatively over recent years (The New Indian Express, 2022).

Governance, Leadership, & Structural Reforms

To ensure transparency, the Odisha Government introduced a leadership rotation policy in April 2025, under which no individual can hold office in SHGs or federations for more than two consecutive terms. Additionally, restructuring of SHGs and federations must occur every three years to broaden participation and leadership opportunities across nearly 35 lakh women members (The New Indian Express, 2025a).

Further, the state initiated a transparency and inclusion drive, ensuring unregistered SHGs are brought under monitoring systems and expanding SHG coverage by enrolling 4.12 lakh additional rural households. Fresh elections for cluster- and block-level federations were also scheduled for 2025 to reinforce democratic governance (The New Indian Express, 2025b).

Supporting Women-Led Enterprises & Market Access

The Odisha Government has invested heavily in enterprise development. Each district-level SHG federation has been allocated a ₹1 crore revolving fund to strengthen entrepreneurship, with plans to establish micro-industrial parks exclusively for SHGs in all 30 districts (The Times of India, 2022).

Market linkages have been encouraged through initiatives such as:

- **Subhadra Shakti Melas:** Exhibitions that showcase SHG products and connect women entrepreneurs to wider markets (MSBLIS, n.d.).
- **Modernisation of Weaving Sector:** In 2025, Mission Shakti partnered with the Weavers' Service Centre to modernize traditional weaving and support the "LakhpatiDidis" initiative—women entrepreneurs aspiring to earn ₹1 lakh annually (The Times of India, 2025a).

Odisha has also emerged as a leader in the Lakhpati Didi Programme, with nearly 17 lakh women already empowered and a target of 25 lakh women by 2027. The programme provides interest-free loans up to ₹10 lakh, enhanced investment support, and promotional platforms such as Mission Shakti cafés and melas (The Times of India, 2025b).

Conclusion

Self-Help Groups have become a cornerstone of rural development and women empowerment in India. They not only provide financial services but also foster collective strength, skill enhancement, and social change. Strengthening SHGs through capacity-building, digital literacy, and sustainable livelihood opportunities can further enhance their role in inclusive development.

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SPECTRAL INTELLIGENCE: HOW HYPERSPECTRAL IMAGING AND AI ARE REWRITING FRUIT QUALITY FORECASTING

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Abstract

Hyperspectral imaging (HSI) and machine learning capture comprehensive spectral data across hundreds of contiguous wavelengths, allowing for quick and non-destructive fruit quality evaluation. Support vector machines, deep neural networks, and partial least squares regression are some of the sophisticated algorithms that convert these spectral fingerprints into precise predictions of firmness, acidity, soluble solids content, and internal flaws, frequently with coefficients of determination (R2) higher than 0.90. Successful commercial applications of the technology include a portable Vis-NIR scanner used for in-field mango monitoring in India, which enables prompt harvest and sorting decisions, and a conveyor-integrated HSI-AI system for real-time grading of apples and strawberries. Advancements in robotic integration, edge AI processing, and sensor miniaturization significantly improve the scalability and effectiveness of HSI–AI solutions. These advancements reduce post-harvest losses and enhance quality assurance for various horticultural crops. To increase prediction accuracy and operational resilience, future research should concentrate on standardising calibration procedures, optimising model transferability between cultivars, and investigating multi-sensor fusion.

Keywords: Hyperspectral imaging, fruit quality assessment, machine learning, post-harvest loss reduction, non-destructive evaluation.

Introduction

Fruit quality significantly affects consumer satisfaction and market value. Internal characteristics are usually quantified using destructive laboratory techniques, such as penetrometers for firmness assessment and refractometers for °Brix measurement. However, these methods are labour-intensive, time-consuming, and often impractical for large volumes (Yang *et al.*, 2025). Producers and packers depend on proxies that offer room for interpretation, such as visual colour, set harvest dates, and random sampling. AI in conjunction with hyperspectral imaging, which records reflectance spectra at hundreds of wavelengths, provides a high-throughput, non-destructive substitute by fusing machine learning with the distinct spectral signature of each fruit, which can vary from visible to near-infrared or short-wave infrared, spectral intelligence forecasts quality indices. These methods enable online grading, storage management, and more intelligent harvest scheduling by rapidly anticipating the interior quality of each fruit (Hasanzadeh *et al.*, 2022).

Hyperspectral Imaging (HSI): A hyperspectral camera (often in the visible to near-infrared range, ~400–1000 nm, or including SWIR up to ~2500 nm) scans fruit to record reflectance at many narrow wavelength bands for each pixel. The output is a "hypercube" (2D image × spectral dimension) volume(Yang *et al.*, 2025). In effect, each pixel has its detailed spectrum. As biochemical compounds (sugars, acids, chlorophyll, water, etc.) and structural features affect light absorption at specific wavelengths, an HSI hypercube contains rich clues about fruit chemistry and maturity (Xiao *et al*., 2025). For example, sugars and organic acids have characteristic near-infrared absorption, skin colour pigments show visible spectral features, and moisture affects broader spectral regions. By contrast, regular RGB cameras only see broad colour; HSI reveals subtle spectral fingerprints invisible to the eye or standard cameras (Elsayed *et al*., 2025).

AI and Chemometrics: Raw HSI data are large and complex; AI methods help build predictive models. Classical chemometric techniques like Partial Least Squares Regression (PLSR) relate spectra to quality traits (Kanwal *et al*., 2025). In recent years, machine learning and deep learning techniques have effectively utilized a wide range of information, such as support vector machines, random forests, artificial neural networks, and convolutional networks. A reference set of fruit, with precisely measured sugar levels, acidity, firmness, and other chemical properties, is scanned using hyperspectral imaging (HSI). Spectral patterns are then precisely mapped to these target parameters using thoroughly trained algorithms (Elsayed *et al*., 2025). Modern neural networks also show the ability to recognize and learn essential spectral properties independently. For example, in one study, ANN, random forest (RF), and decision tree (DT) models were used in HSI data to predict mango sugar, chlorophyll, and firmness.

The advantages of HSI+AI include:

- **Non-destructive multi-parameter sensing:** A single HSI scan can inform on multiple qualities at once (e.g. sugar, acidity, dry matter, anthocyanins) without cutting or destroying the fruit (Hasanzadeh *et al*., 2022).
- **Spatial mapping:** HSI not only gives an average value but also reveals spatial variations (e.g. bruises or early decay spots). Machine vision models can localise defects while analysing the fruit (Chandak & Rawat, 2024).
- **High accuracy:** Recent reports often show strong correlations (R^2 ~0.9–0.99) between HSI-based predictions and lab measurements. For instance, Hasanzadeh*et al.* (2022) reported models for Red Delicious apples with R^2 up to 0.99 in predicting pH, soluble solids content (SSC) and acidity. These near-perfect fits illustrate the potential precision.
- **Real-time capability:** With fast cameras and optimized models, HSI+AI can operate on packaging lines or even in the field (proximal sensing), enabling real-time quality monitoring (Kanwal *et al*., 2025).

Technical workflow: A fruit is placed before a handheld or con HSI (Hyperspectral Imaging) system, or a belt. Fruit's characteristics include its quality, ripeness, and potential defects, which are analyzed in detail. It captures a wide range of wavelengths beyond the visible spectrum. The data obtained can help make informed decisions regarding sorting, grading, and quality control processes in the fruit industry. The camera collects a hyperspectral cube (often requiring scanning time from milliseconds to seconds). Pre-processing (noise filtering, normalization) is applied (Hasanzadeh *et al*., 2022). Then a trained AI model (PLSR, SVM, CNN, etc.) ingests the spectra (or derived "spectral indices") and outputs quality metrics or classes. For example, spectral indices emphasizing water-absorption bands can help predict dry matter, while NIR bands correlate with SSC. End-users see the predicted quality scores or categories (ripe/not ripe, sweet/dull, normal/defective) and can sort fruit accordingly.

Example capabilities: HSI+AI has been shown to predict fruit qualities such as total soluble solids (°Brix), titratable acidity, dry matter, firmness, chlorophyll and other pigments, and even nutrient or contaminant levels (Wang *et al*., 2024). It can also classify maturity stages or detect early defects (bruises, fungal spots) that are invisible on the surface. In effect, spectral intelligence turns unseen chemical differences into actionable quality forecasts.

Case Study 1: Mango and Strawberry Ripeness
A recent international study (Egypt and Australia) demonstrated HSI+AI for non-destructive ripeness assessment of two popular fruits, **mango** ("Succari" cultivar) and **strawberry** ("Florida" cultivar). The researchers scanned many fruits at different ripening stages using a spectral camera, and measured biochemical parameters in the lab (chlorophyll, soluble solids content (TSS), firmness for mango; colour L*, b* values, TSS, firmness for strawberry). They computed both established and novel spectral reflectance indices (combinations of wavelengths sensitive to each trait), and then trained machine-learning models (artificial neural networks, random forests, decision trees) on this data (Elsayed *et al*., 2025).

For mango, the best models achieved **R^2 ≈ 0.92–1.00** on the training set and **R^2 ≈ 0.93–0.98** on testing for predicting chlorophyll content, TSS and firmness. Strawberry parameters were predicted slightly less tightly (e.g. R^2 up to 0.91) but still robustly. The HSI+AI system could almost perfectly match laboratory °Brix and firmness readings from just the hyperspectral image. Notably, the approach used off-the-shelf HSI hardware and standard ML tools, indicating practicality (Gao &Xie, 2024). This case shows how spectral intelligence can rapidly estimate internal fruit quality across a large batch, information that would conventionally require destructive lab tests for many samples. Such capability can guide growers on optimal harvest time (ripe vs underripe), or allow packers to sort fruit by sweetness without sampling.

Case Study 2: Mango and Apple Quality in India
India – the world's leading mango producer – also invests in high-tech grading to boost quality. Mango export from India has been limited by inconsistent manual grading and defects. In order to automate fruit sorting and grading, researchers are increasingly using artificial intelligence and spectral analysis. Nithya *et al*. (2022) created a deep learning-based visual system to identify the surface of mangoes. Using an extensive image database, they trained a convolutional neural network to classify mango fruit into "good" or "defective" classes. The system achieved **98% accuracy** in classifying quality levels, vastly improving over human sorting reliability.

Crucially, hyperspectral imaging is now entering Indian orchard and packhouse trials. Chandak&Rawat (2024) conducted a pilot on **apple bruising** using an HSI camera and a YOLOv5 deep-learning network. They scanned Honeycrisp and Red Delicious apples with a ResononPika NIR-320 hyperspectral camera and induced subtle bruises by dropping. A YOLO-based CNN was trained on the spectral images to localize bruised areas. The model's accuracy in detecting bruising was 96.2%, with a mean average precision of 0.95. In practice, this means almost every bruised apple was correctly flagged. Combined with the mango work above, these Indian case studies demonstrate that HSI+AI can be woven into local quality-control systems. Non-destructive scanners might soon be used in Indian packing lines to automatically reject blemished fruit, or even handheld probes for field checks. Together, they show the feasibility and impact of spectral intelligence in India's fruit industry.

Applications: HSI+AI is maturing from lab studies to real-world use. In packing facilities, hype spectral cameras can be mounted on conveyors to sort fruit by sweetness, ripeness or defects (Nithya *et al*., 2024). For example, a kiwifruit packer could use the HSI model to separate batches by firmness class before export (as recently demonstrated with >91% accuracy). On farms, portable or drone-mounted HSI can scan canopy fruit to predict harvest windows and yields. Post-harvest, HSI can monitor stored fruit to anticipate spoilage, *e.g.* by detecting early decay-related spectral changes, which helps in dynamic shelf-life forecasting. Across the supply chain, these systems enable **quality forecasting**. Growers and retailers get a warning of future fruit quality, reducing waste and ensuring consumers receive consistent products.

Advantages for the industry: Spectral intelligence allows **single-pass quality assessment**. One HSI scan yields multi-dimensional quality data, unlike single-measure sensors. This can shorten inspection lines and provide traceable records (image archives) for each fruit lot. Automated H I systems remove human bottlenecks in practice: machines work continuously and objectively under variable lighting (Gao &Xie, 2024). They can sort much larger volumes than manual grading, without fatigue. For example, a food processor could ensure that only fruits above a sweetness threshold go into premium products or that of-spec fruit are rerouted to juicing or other uses.

Future directions: The field is rapidly advancing. Costs of hyperspectral cameras and computing are falling, making deployment more feasible. Research is adapting to different cultivars and **lightweight algorithms** suitable for embedded hardware. There is a move toward smartphone-friendly sensors or small multispectral devices targeting eyeglasses. Standardization of spectral indices and calibration methods is also progressing, to allow models trained in one setting to transfer elsewhere (Hasanzadeh *et al*., 2022).

Limitations and expectations: While highly promising, HSI+AI is not magic. Accuracy depends on good training data and controlled imaging conditions (Lee *et al*., 2024). For instance, a machine might predict internal quality but requires occasional calibration against lab data. However, as demonstrated in the cited studies, the gains are real: non-destructive for casting with R^2 often above 0.9 is a notable advance over conventional guesswork.

Outlook: The fusion of spectral imaging and AI is poised to transform fruit quality management. It enables data-driven decisions at all stages – harvest, packing, storage, and retail and can significantly reduce waste by catching underripe or damaged fruit early. As Yang *et al.* (2025) conclude, hyperspectral imaging plus deep learning "promote intelligent and precise fruit quality inspection," which will be crucial for food safety and supply chain efficiency. Spectral intelligence is thus an emerging cornerstone of innovative horticulture, and its impact will only grow as sensors become ubiquitous and algorithms more refined.

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ROLE OF PROBIOTICS IN SUSTAINABLE AQUACULTURE

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Abstract
Probiotics have emerged as a pivotal solution for sustainable aquaculture, addressing key challenges such as disease outbreaks, environmental degradation, and antibiotic resistance. By introducing beneficial microorganisms into aquatic systems, probiotics not only enhance the health and growth of fish and shellfish but also improve water quality and ecosystem stability. Their multifaceted benefits position them as essential bio-tools in the transition toward more sustainable, eco-friendly, and productive aquaculture practices.

Key Word : Probiotics, Aquaculture, Sustainability, Disease resistance, Immune stimulation.

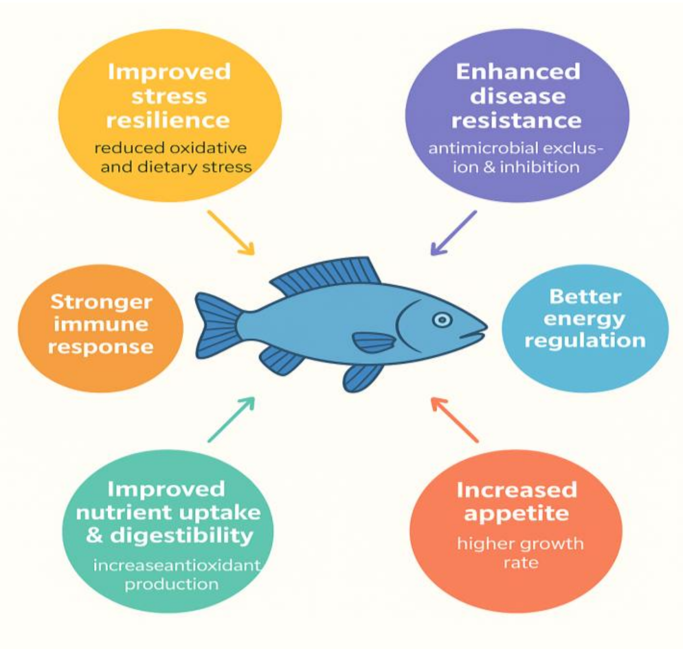
Introduction
Aquaculture is a vital contributor to global food security, offering a reliable source of protein and livelihood for millions. However, as the industry grows to meet the rising demand, it faces challenges like disease outbreaks, environmental degradation, and antibiotic resistance. In this context, probiotics have emerged as a sustainable and eco-friendly alternative to chemical therapeutics and antibiotics. Probiotics are live beneficial microorganisms that, when administered in adequate amounts, provide health benefits to the host. In aquaculture, their roles extend beyond disease control they enhance growth performance, improve digestion, boost immunity, and even help in maintaining water quality.

1. **What Are Probiotics and How Do They Work?**
   Probiotics are live, beneficial microorganisms, commonly bacteria or yeasts, that when administered in adequate amounts, provide health benefits to the host organism. In aquaculture, typical probiotic genera include *Lactobacillus*, *Bacillus*, *Enterococcus*, and *Saccharomyces*. These microbes work by modulating the gut microbiota, enhancing digestive enzyme secretion, producing antimicrobial compounds, and competing with pathogens for adhesion sites in the intestinal tract. The result is improved nutrient absorption, growth performance, and a strengthened immune system in the cultured aquatic species.

- **Gut Microbiota Modulation**: Probiotics help maintain a healthy microbial balance in the gastrointestinal tract (GIT), promoting beneficial microbes like *Lactobacillus* and suppressing harmful pathogens. A balanced gut flora enhances nutrient absorption and overall health(Madhulika *et al.*, 2025).

- **Immune Stimulation**: They modulate the immune system by interacting with intestinal cells and promoting the production of immune-related molecules such as lysozymes and bacteriocins. This enhances the host's resistance to stress and infections(Dawood *et al*., 2019).
- **Enzyme Production**: Probiotics can secrete digestive enzymes such as amylases, proteases, and lipases, improving feed digestibility and nutrient uptake.
- **Competitive Exclusion**: They outcompete pathogens for adhesion sites on intestinal walls, preventing colonization and infection.

2. **Benefits of Probiotics in Sustainable Aquaculture**



a. Growth Promotion and Feed Efficiency

Probiotics enhance the digestion process, resulting in better feed conversion ratios (FCR). Fish and shrimp supplemented with probiotics like *Bacillus subtilis* or *Saccharomyces cerevisiae* show significantly improved weight gain, specific growth rates (SGR), and nutrient assimilation. Studies have reported increased enzyme activities in the gut and improved growth performance across species like sea bass, rohu, tilapia, and white shrimp.

b. Disease Resistance and Immunity

Disease outbreaks pose a major threat to aquaculture sustainability. Probiotics help reduce dependence on antibiotics by stimulating innate immunity and producing antimicrobial compounds. These include bacteriocins, hydrogen peroxide, and organic acids, which inhibit pathogens like *Aeromonas*, *Vibrio*, and *Streptococcus*. Enhanced levels of lymphocytes and granulocytes have been observed in probiotic-fed fish, indicating a stronger immune response.

c. Environmental Impact and Water Quality

One of the often-overlooked benefits of probiotics is their role in improving water quality. Certain probiotic strains aid in decomposing organic waste, reducing toxic compounds like ammonia and nitrite, and recycling nutrients in the culture system. This creates a more stable and healthy environment for aquatic animals, particularly in intensive or recirculating aquaculture system.

3. Application Strategies in Aquaculture

Aspect	Details	Notes
Application Methods	1. Via feed (most common, colonizes gut) 2. Directly into water (hatcheries & larval rearing)	Prevents early-stage infections
Advanced Approaches	1. Multi-strain probiotic combinations 2. Synbiotics (probiotics + prebiotics)	Maximizes health benefits & microbial diversity
Timing & Dosage	Continuous feeding for 4–8 weeks	Proven beneficial for fish & shrimp
Heat-Stable Spores	Bacillus species spores ensure viability	Stable during feed processing & storage

Conclusion

In the journey toward sustainable aquaculture, probiotics represent a multifaceted solution. They improve growth, enhance immunity, and reduce the reliance on antibiotics while also contributing to better environmental management. With rising interest and research investment, especially in metagenomics and microbial ecology, probiotics are set to play an even greater role in future aquaculture practices. For policymakers, researchers, and farmers alike, embracing probiotic-based approaches is not just a health decision—it's an ecological and economic imperative.

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ROLE OF NANOFERTILIZERS IN FOOD, NUTRITION AND ENVIRONMENT SECURITY

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Abstract

Nanofertilizers hold significant promise for enhancing food security, nutrition, and environmental sustainability. They improve nutrient uptake efficiency dramatically compared to conventional fertilizers, enabling smaller dosages while maintaining or increasing crop yields and nutritional quality. This efficiency reduces nutrient losses to soil and water, thus decreasing environmental pollution such as soil degradation and water contamination. Nanofertilizers present a promising, sustainable advancement for improving food production, nutrition, and environmental security by enhancing nutrient use efficiency and reducing environmental impacts. This paper focuses on role of nanofertilizers in food, nutrition and environment security

Introduction

Nanofertilizers play a significant role in enhancing food security, nutrition, and environmental sustainability by improving nutrient uptake efficiency and reducing negative environmental impacts. They are fertilizers engineered at the nanoscale (1–100 nm) that allow precise, controlled release of nutrients to plants, thereby increasing fertilizer use efficiency and crop yield while minimizing nutrient loss and environmental pollution.

Key roles of nanofertilizers in food, nutrition, and environment security include:

- **Improved Nutrient Uptake Efficiency (NUE):** Nanofertilizers increase NUE up to threefold compared to conventional fertilizers. This improved efficiency means crops absorb nutrients more effectively, resulting in higher yields and better crop nutritional quality, which is important for addressing "hidden hunger" (micronutrient deficiencies).
- **Reduction in Fertilizer Dosage and Environmental Pollution:** Nanofertilizers require smaller dosages (e.g., 40 kg/hectare vs. 200 kg/hectare for conventional fertilizers), leading to less runoff, reduced water and soil pollution, and lower greenhouse gas emissions like nitrous oxide and methane. Their slow and controlled nutrient release further minimizes nutrient losses and environmental degradation, making agriculture more sustainable.
- **Enhanced Crop Growth and Stress Adaptation:** Nanofertilizers help plants adapt better to abiotic stresses (e.g., drought, salinity) and biotic stresses (pests, diseases), thereby improving resilience and reducing yield losses caused by these stressors.
- **Improvement in Crop Nutritional Quality**: By increasing nutrient availability and uptake, nanofertilizers help biofortify crops, improving their vitamin and mineral content, thereby contributing to nutritional security.
- **Environmental Safety and Food Security**: Nanofertilizers are considered safe with the correct application and follow eco-friendly practices. They contribute to greater food

security by promoting sustainable agriculture practices that protect soil and water resources.
- **Cost Efficiency and Precision Agriculture:** Their smaller required dosage and targeted delivery reduce input costs and environmental footprint, aiding precision nutrient management for enhanced productivity and environmental protection.

In summary, nanofertilizers contribute to food, nutrition, and environmental security by enabling higher crop yields and improved nutritional quality with lower environmental impact through enhanced nutrient use efficiency, controlled nutrient release, and reduced chemical runoff.

Environmental impacts of nanofertilizer use

The environmental impacts of nanofertilizer use are generally positive compared to conventional fertilizers but are not without concerns and limitations.

Positive environmental impacts:

- Nanofertilizers improve nutrient use efficiency (NUE) by releasing nutrients slowly and in a controlled manner, significantly reducing nutrient losses via leaching, runoff, and gaseous emissions (such as ammonia volatilization and nitrous oxide), which are common with traditional fertilizers. This leads to less soil and water pollution and lower greenhouse gas emissions.
- Their targeted delivery reduces the quantity of fertilizer needed, decreasing the environmental footprint and mitigating eutrophication risks in water bodies caused by nutrient runoff.
- Nanofertilizers can help maintain soil fertility and promote sustainable agriculture through enhanced nutrient absorption by plants and minimized environmental contamination.
- Compared to conventional granular nitrogen fertilizers, nanofertilizers reduce nitrogen losses to the atmosphere and water, contributing to less air pollution and water eutrophication in grasslands and cropping systems.

Concerns and potential negative impacts:

- The small size of nanoparticles allows them to penetrate biological systems more deeply, raising concerns about nano-toxicity to soil microorganisms, plants, animals, and potentially humans. The full safety profile of nanofertilizers is still under research.
- Toxic effects may differ depending on nanoparticle composition—metal and metal oxide nanoparticles tend to be more toxic than biologically produced or organic nanoparticles.
- There is a lack of sufficient regulation, risk management frameworks, and standardized formulations for nanofertilizers, leading to quality control issues and potential environmental risks from unregulated or mislabeled products.
- The high cost and production scalability of nanofertilizers are hurdles that may affect their widespread adoption, which might inadvertently lead to increased use of less efficient conventional fertilizers with higher environmental impacts in some regions.
- Overuse or supra-optimal doses of nanofertilizers may negatively affect crop growth, soil health, and environmental outcomes, so proper dosing and application techniques are necessary.

In summary, nanofertilizers offer substantial environmental benefits by enhancing nutrient efficiency and reducing pollution compared to conventional fertilizers. However, concerns about nanoparticle toxicity, regulation, cost, and application standards remain challenges to their sustainable use and require further research and policy development.

If you want, I can provide details on safety guidelines or recent advances in mitigating the risks associated with nanofertilizers.

Greenhouse gas emissions from nanofertilizer application

Nanofertilizer application generally greenhouse gas (GHG) emissions such as methane (CH_4) and nitrous oxide (N_2O) compared to conventional fertilizers. This is mainly because nanofertilizers improve nitrogen use efficiency through slow and controlled nutrient release, reducing losses that cause GHG emissions.

Key findings include:

- Studies showed that applying nano urea foliar sprays with reduced overall nitrogen doses resulted in significantly lower methane and nitrous oxide emissions compared to full doses of conventional urea fertilizer.
- Nanofertilizers enhance soil carbon sequestration by improving organic matter content and microbial activity, contributing to lower carbon dioxide (CO_2) emissions from soil.
- The slow-release and targeted delivery mechanisms reduce nitrogen volatilization and leaching, major sources of nitrous oxide, a potent GHG.
- Nanomaterials based on titanium dioxide, zinc oxide, and zeolite have been evaluated for their potential to mitigate N_2O and CO_2 emissions while improving nutrient efficiency.

Overall, nanofertilizers offer a promising sustainable agricultural practice that can contribute to mitigating climate change by lowering greenhouse gas emissions associated with fertilizer use.However, continued research on their long-term environmental impact and careful management are needed to ensure safety and maximize benefits.

Innovative nanofertilizer formulations for GHG reduction

Innovative nanofertilizer formulations for reducing greenhouse gas (GHG) emissions focus on enhancing nutrient use efficiency with controlled, slow, and targeted nutrient release to minimize losses that produce GHGs such as nitrous oxide (N_2O) and methane (CH_4).

Key examples of such formulations include:

- Hybrid Nanofertilizers (HNF): Urea-modified hydroxyapatite nanoparticles combined with micronutrients like copper, iron, and zinc create slow-release fertilizers. These nanoparticles sustainably release nitrogen, calcium, phosphate, and micronutrients, substantially improving nutrient uptake and reducing fertilizer application rates by up to 90%. This slow release lowers nitrogen losses that would otherwise convert into N_2O emissions.
- Nano-NPK and Nano-Nitrogen Fertilizers: Nano-engineered macronutrients (N, P, K) and micronutrients in forms like nano-chelated compounds or nano-zeolite composites enable precise delivery and prolonged nutrient availability, curbing nutrient runoff and volatilization that lead to GHG emissions.
- Nano-Biofertilizers: Combining nanoparticles with biofertilizers (microorganisms) encapsulated in biopolymers like chitosan or polysaccharides enhances nutrient delivery and plant stress resilience. This method supports nitrogen fixation and improves photosynthesis, indirectly contributing to lowered GHG emissions.

- Nano-encapsulation and Coatings: Use of biopolymer coatings such as chitosan to encapsulate nutrients enables controlled nutrient release synchronized with plant uptake patterns, reducing excess nitrogen in the soil and consequent N2O emissions.

Such innovative nanofertilizers not only increase nutrient use efficiency, often reducing fertilizer dosage by 50% or more, but also improve crop uptake and yield, contributing to sustainable agriculture while mitigating climate change by lowering methane and nitrous oxide emissions from soils.

Continued research is ongoing to optimize formulation, dosage, and application methods to maximize environmental benefits while ensuring safety and cost-effectiveness.

In summary, hybrid nanofertilizers based on urea-modified hydroxyapatite with micronutrient doping, nano-NPK formulations, and nano-biofertilizer systems using biopolymer encapsulation represent state-of-the-art innovations aimed at reducing GHG emissions through improved nutrient management.

Greenhouse gas reduction mechanisms in nanofertilizer use

The main mechanisms by which nanofertilizer use reduces greenhouse gas (GHG) emissions are:

- Improved Nitrogen Use Efficiency (NUE): Nanofertilizers release nitrogen slowly and in a controlled manner, closely matching plants' nutrient uptake needs. This reduces nitrogen losses into the environment via leaching, runoff, and gaseous emissions such as nitrous oxide (N2O) and ammonia volatilization, which are potent GHGs.
- Reduced Nitrogen Losses and Volatilization: By minimizing excess nitrogen in the soil, nanofertilizers cut down emissions of N2O and nitrogen oxides that arise from conventional fertilizer overuse.
- Enhanced Soil Carbon Sequestration: Nanoparticles in nanofertilizers improve soil organic matter content, microbial activity, and soil aggregation. This enhances the soil’s ability to sequester carbon dioxide (CO2), another major GHG.
- Targeted Nutrient Delivery and Slow Release: Innovations like nano-encapsulation (e.g., nutrient coatings with biopolymers) synchronize nutrient availability with plant demand, reducing nutrient wastage and subsequent GHG emissions from off-target nitrogen transformations.
- Synergistic Effects with Biofertilizers: Nanobiofertilizers combine nanomaterials with beneficial microorganisms to enhance nitrogen fixation and nutrient uptake, indirectly lowering N2O emissions by stabilizing nitrogen in plant-available forms.

In summary, nanofertilizers reduce GHG emissions primarily by improving nutrient delivery efficiency, minimizing nitrogen losses that lead to N2O and other nitrogenous emissions, fostering better soil carbon storage, and by enabling precision nutrient management through smart formulations and biotechnological integrations. These mechanisms make nanofertilizers a promising tool for sustainable agriculture and climate change mitigation, although ongoing research is needed to fully optimize and ensure their environmental safety.

Nanofertilizers positively impact soil organic carbon (SOC) levels by improving soil fertility and enhancing biological processes that promote carbon storage in soil. Their nanoscale properties allow controlled and slow nutrient release, which increases nutrient use efficiency and reduces nutrient losses to the environment. This process supports greater plant growth and biomass production, leading to more organic carbon inputs into the soil through root exudates and plant residues.Key points on the impact of nanofertilizers on soil organic carbon include:

- Nanofertilizers stimulate soil microbial activity and enzymatic functions (e.g., urease, phosphatase) that enhance the accumulation and stabilization of organic matter in soil aggregates, increasing SOC retention.
- Their controlled nutrient release reduces leaching and nutrient runoff, which helps maintain soil fertility and supports long-term organic matter buildup.
- Improved nutrient management fosters healthier plants with increased photosynthesis, adding more organic carbon to the soil ecosystem.
- Some nanofertilizer formulations also improve soil structure and water retention, further aiding carbon sequestration and soil health.
- Studies show nanofertilizers can increase soil organic matter content and improve nutrient availability more effectively than conventional fertilizers, which helps boost crop productivity sustainably.

However, soil organic carbon enhancement depends on nanoparticle type, dosage, and soil characteristics, as nanofertilizer interactions with soil microorganisms and organic components regulate their mobility and effectiveness.

In summary, nanofertilizers contribute to higher soil organic carbon levels by improving nutrient efficiency, stimulating beneficial soil microbial processes, and enhancing plant growth and organic matter input, thus supporting sustainable soil fertility and carbon sequestration in agroecosystems.

If desired, I can provide more examples of specific nanofertilizer types or formulations that optimize soil organic carbon improvement.

Soil microbial changes from nano-fertilizer use

Nanofertilizer use causes notable changes in soil microbial communities, with both positive and some potential negative effects, depending on nanoparticle type, dosage, and application method. Key findings include:

- Enhanced Microbial Activity and Diversity: Nanofertilizers can stimulate soil microbial populations, including bacteria, fungi, and actinomycetes, by improving nutrient availability and uptake. For example, nano-urea sprays combined with reduced nitrogen doses maintained or enhanced microbial biomass carbon and diversity, positively affecting groups like Actinobacteria, Bacteroidia, and Proteobacteria, which are important for nutrient cycling and crop yield.
- Influence on Rhizosphere Microbes: Nanofertilizers affect the rhizosphere microbial community structure, which is critical for plant nutrient processes like nitrogen fixation and phosphate solubilization. Certain nanomaterials may alter microbial attachment to roots or shift bacterial and fungal populations variably, sometimes enhancing beneficial microbes and other times reducing microbial counts depending on nanoparticle properties.
- Toxicity and Disruption Risks: Some nanoparticles, especially metal or metal oxide types, may interfere with biological processes and microbial life cycles, potentially causing toxicity to soil microbes if applied excessively or improperly. Persistent accumulation of

nanoparticles could pose long-term risks for soil microbial diversity and functions, but these effects are still under study.
- Improved Soil Functions: By promoting microbial enzyme activities (e.g., urease, phosphatase) and supporting microbial-mediated nutrient cycling and organic matter decomposition, nanofertilizers can enhance soil fertility and sustainability under proper management.
- Synergistic Effects with Biofertilizers: When combined in nano-biofertilizer formulations, nanoparticles and beneficial microbes can improve plant stress tolerance and soil health, further supporting microbial community resilience and productivity.

In summary, nanofertilizers generally promote soil microbial biomass, diversity, and function, which benefits nutrient cycling and crop productivity, but careful dosing and monitoring are essential to avoid potential nanoparticle toxicity and ensure long-term soil microbial health.

Soil microbial resilience after nano-fertilizer application

Soil microbial resilience after nanofertilizer application appears to be generally positive, with improvements in microbial population, diversity, and function when nanofertilizers are properly formulated and applied. Research shows that nanofertilizers can stimulate the growth of beneficial soil bacteria and fungi by providing nutrients in readily available forms, thereby increasing microbial biomass and activity in the soil after crop harvest. This enhanced microbial resilience promotes nutrient cycling and soil fertility, ultimately supporting crop productivity.

Key points on soil microbial resilience include:

- Foliar application of nanofertilizers increases soil bacterial and fungal populations as well as microbial biomass carbon, which indicates healthier and more active soil microbial communities.
- Nanofertilizers improve nutrient availability, which supports beneficial microbes like Actinobacteria, Bacteroidia, and Proteobacteria, essential for nutrient transformations and plant nutrient uptake.
- Nanofertilizers enhance soil enzymatic activities and microbial diversity, contributing to better soil biological health and ecosystem functioning.
- Some concerns exist regarding potential toxicity at high or inappropriate nanoparticle doses, especially with metal or metal oxide nanoparticles, but with proper dosing, nanofertilizers appear safe and supportive of microbial resilience.
- Nanofertilizers also show promise in improving microbial resilience by stimulating beneficial microbial populations and enhancing resistance to environmental stresses.
- Overall, nanofertilizer use under careful management supports soil microbial community recovery and stability (resilience) after application, fostering sustainable nutrient cycling and soil health.

In summary, nanofertilizers enhance soil microbial resilience by boosting microbial biomass, diversity, and beneficial functions through improved nutrient supply and soil conditions, though proper application is crucial to avoid negative impacts.

Long-term effects of nano-fertilizers on microbes

The long-term effects of nanofertilizers on soil microbial communities are generally positive but with some caution due to possible toxicity and accumulation risks.

Key points from recent research include:

- Enhanced Microbial Diversity and Activity: Long-term use of nanofertilizers, especially combinations like nano-nitrogen and nano-zinc, showed improvements in soil microbial biomass carbon and diversity, promoting beneficial microbial groups such as Actinobacteria, Bacteroidia, and Proteobacteria that are important for nutrient cycling and soil health. Foliar sprays with reduced conventional nitrogen doses yet supplemented with nanofertilizers sustained microbial activity and improved crop yield in wheat and maize systems.
- Sustainable Nutrient Management: Nanofertilizers can reduce the required chemical fertilizer dosage by 25-50% while maintaining or enhancing growth and microbial niches, which supports long-term soil fertility and ecosystem function.
- Potential Toxicity and Accumulation Concerns: Some nanoparticle types, especially metal and metal oxide nanoparticles, may exhibit toxicity to soil microbes at higher doses or with prolonged exposure. Long-term persistence of nanoparticles in soil could affect microbial community structure and function, possibly impairing soil health if not well managed. However, organically produced or biologically-derived nanoparticles tend to be less toxic.
- Impact on Biofertilizer Microbes: Nano-biofertilizer formulations combining beneficial microbes with nanoparticles can enhance microbial tolerance to stresses, improve nutrient cycling, and support microbial longevity, indicating synergistic benefits in the long term.
- Research Gaps and Regulation Needs: Despite promising findings on microbial benefits, comprehensive data on environmental fate, persistence, and long-term ecological effects of nanofertilizers on microbes are limited. Regulatory frameworks and standardized formulations are still under development to ensure safe, sustainable use at scale.

In summary, long-term nanofertilizer application tends to promote a more diverse and active soil microbial community supporting nutrient cycling and crop productivity when applied appropriately. However, potential nano-toxicity and accumulation require careful dosing, monitoring, and further research to guarantee environmental safety and optimal microbial resilience.

Long-term soil health under nano-fertilizer use

The long-term effects of nanofertilizers on soil health are generally positive, with several benefits but some considerations for caution.

Key positive impacts include:

- Enhanced soil fertility and nutrient levels: Nanofertilizers improve nutrient use efficiency, reduce nutrient leaching and runoff, and provide controlled slow nutrient release, which sustains nutrient supply to plants and microbes over time. This leads to increased soil nutrient availability and improved soil ecological conditions.
- Stimulation of soil microbial activity and diversity: Nanofertilizers promote the growth and diversity of beneficial soil microorganisms, such as bacteria and fungi important for nutrient cycling, organic matter decomposition, and soil structure maintenance. This enhances soil biological health and ecosystem functioning.
- Improved soil structure and organic matter content: Through promoting microbial activities and humic acid production, nanofertilizers help increase soil aggregate stability, organic carbon retention, and moisture regulation, all contributing to better soil quality and resilience.

- Reduced chemical fertilizer dependency: By enabling precise, efficient nutrient delivery, nanofertilizers can lower the need for conventional chemical fertilizers, which often harm soil health through overuse.

Considerations and challenges for long-term soil health under nanofertilizer use:

- Nanoparticle accumulation and persistence: Nanoparticles tend to accumulate slowly in soil because of their stable nature, which might affect nutrient mobility and microbial interactions if accumulation becomes excessive over decades. Their long-term fate in soil is still under research.
- Potential nano-toxicity risks: Some metal or metal oxide-based nanoparticles may be toxic to certain soil microbes or disrupt microbial community balance if overdosed or poorly managed. Proper formulation and dosage are important to avoid negative effects.
- Need for regulatory frameworks and monitoring: As nanofertilizers are novel, standardized regulations, risk assessments, and long-term environmental monitoring are necessary to ensure safe soil management and sustainable use.

In summary, with proper application, nanofertilizers enhance long-term soil health by improving nutrient availability, stimulating beneficial microbial communities, and supporting soil structure and fertility. However, ongoing research and cautious management are essential to mitigate risks related to nanoparticle accumulation and toxicity to guarantee sustainable soil ecosystems over time.

Concluding Remarks

Nanofertilizers hold significant promise for enhancing food security, nutrition, and environmental sustainability. They improve nutrient uptake efficiency dramatically compared to conventional fertilizers, enabling smaller dosages while maintaining or increasing crop yields and nutritional quality. This efficiency reduces nutrient losses to soil and water, thus decreasing environmental pollution such as soil degradation and water contamination. Nanofertilizers can also mitigate greenhouse gas emissions (e.g., nitrous oxide, methane) from fertilizer use, contributing to better climate outcomes. Economically, they offer cost-effectiveness for small-scale farmers through lower input requirements and potential for higher revenues. These benefits position nanofertilizers as a green and sustainable opportunity to increase crop productivity, improve food and nutritional security, and safeguard environmental health. However, challenges remain before widespread adoption. Most nanofertilizer technologies are still largely in experimental stages with limited field data, making their real-world performance and environmental impact not fully understood.

Research gaps include understanding molecular modes of action, toxicity concerns to humans and ecosystems, and potential long-term effects. Regulatory frameworks and standardization are insufficient, and the higher current costs alongside inconsistent production quality hinder large-scale application. There is also a need to ensure genuine nanoscale formulations rather than marketed micron-sized products. Responsible development and more extensive multi-disciplinary research are critical to address safety, efficacy, and commercial viability issues.

Nanofertilizers present a promising, sustainable advancement for improving food production, nutrition, and environmental security by enhancing nutrient use efficiency and reducing environmental impacts. Yet, realization of their full potential depends on overcoming technological, safety, regulatory, and economic challenges through continued research, innovation, and standardized practices.

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COMMERCIALLY IMPORTANT MARINE ORNAMENTAL FISHES IN PAZHAVERKADU REGION

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Introduction

Marine ornamental fishes are a diverse group of aesthetically attractive species collected from coral reefs, lagoons, and coastal habitats worldwide. These species hold high economic value in the global aquarium trade due to their vibrant colors, unique behaviors, and adaptability to captive conditions (Wabnitz *et al*., 2003). Pazhaverkadu, also known as Pulicat, is a coastal estuarine ecosystem located along the Coromandel Coast of Tamil Nadu, India, and is recognized for its rich biodiversity and vibrant fishery resources. Among these, marine ornamental fishes hold significant commercial value due to their high demand in the domestic and international aquarium trade. The unique ecological conditions of the region, characterized by the estuary's mix of saline and freshwater influences, provide an ideal habitat for a variety of brightly coloured and ecologically important species. These ornamental fishes not only contribute to the livelihoods of local fishing communities through sustainable harvest and trade but also play a crucial role in maintaining ecological balance. The study of commercially important marine ornamental fishes in the Pazhaverkadu region is therefore essential to understand their diversity, economic potential, and the need for effective conservation and management strategies.

Commercially Important Families and Species

Angel fish

The angel fish (*Pomacanthus semicirculatus* and *P. annularis*) is one of the most visually striking marine ornamental species found in the Pazhaverkadu region, characterized by its vibrant colour patterns and laterally compressed body that make it highly desirable in the global aquarium trade. These species inhabit coral-rich and rocky areas within the estuarine and nearshore marine zones, where they play an ecological role as grazers. Angelfish primarily feed on sponges, algae, tunicates, and small invertebrates, using their specialized mouths to nip at sessile organisms, thereby contributing to the health and balance of the reef ecosystem (Allen *et al*., 1998). In the Pazhaverkadu ornamental fishery, angelfish fetch a relatively high market price due to their demand in export markets, with larger and vividly coloured individuals commanding premium value. Sustainable collection practices are crucial to prevent population decline, as overharvesting and habitat degradation can threaten their availability. Their economic significance, coupled with their ecological role, underscores the importance of targeted conservation measures and regulated trade in the region (Rhyne *et al*., 2012; Wabnitz *et al*., 2003).

Butterfly fishes

Butterflyfishes, notably species such as *Chaetodon auriga* (Threadfin Butterfly fish) and *Chaetodon collare* (Collared Butterfly fish), are among the most visually captivating ornamental fishes found in the coral-associated and nearshore marine habitats of the Pazhaverkadu region. Recognized for their bright colours, disc-shaped bodies, and distinct patterns, these fishes are highly prized in the international aquarium trade. In their natural habitat, butterflyfishes exhibit specialized feeding habits, primarily consuming coral polyps, small invertebrates, and algae, with some species showing strong coral-dependence, making them important indicators of reef health (Pratchett, 2005).In the Pazhaverkadu ornamental fishery, butterflyfishes contribute significantly to fisher incomes, though their slow growth and coral reliance make them vulnerable to overexploitation and habitat degradation. Therefore, adopting regulated harvest practices and promoting habitat conservation are essential for sustaining both their populations and commercial value in the long term.

Seahorses (Family Syngnathidae)

Seahorses, particularly *Hippocampus kuda* (Spotted Seahorse) and *Hippocampus trimaculatus* (Three-spot Seahorse), are notable ornamental and medicinally valued species recorded in the estuarine and seagrass habitats of the Pazhaverkadu region. These slow-moving, upright-swimming fishes possess a prehensile tail that allows them to anchor onto seagrass blades, mangrove roots, or coral branches. Their feeding habit is highly specialized they lack teeth and a stomach, relying on a rapid suction feeding mechanism to consume small crustaceans such as copepods, amphipods, and mysid shrimps, along with other planktonic organisms (Foster & Vincent, 2004). In the ornamental trade, seahorses hold significant commercial value due to their unique morphology and symbolic appeal, while in certain markets they are also in demand for traditional medicine. In Pazhaverkadu, they are collected in small numbers for the aquarium industry and occasionally for dried trade, contributing supplemental income to local fishers. However, their low reproductive rate, site fidelity, and habitat vulnerability make them highly susceptible to overexploitation. As a result, sustainable harvest limits and protection under international trade regulations, such as CITES Appendix II, are crucial for ensuring their long-term conservation (Vincent *et al*., 2011; Wabnitz *et al*., 2003).

Cardinal fishes (Family Apogonidae)

Cardinal fishes (Family: *Apogonidae*), particularly *Pterapogon kauderni* (Banggai Cardinal fish) and *Apogon leptacanthus* (Threadfin Cardinalfish), are small, nocturnal marine ornamental fishes occurring in sheltered reef areas, mangrove edges, and seagrass beds of the Pazhaverkadu region. They are characterized by their distinctive body markings, peaceful temperament, and mouthbrooding reproductive strategy, which makes them attractive to aquarium hobbyists. Cardinalfishes

primarily feed on small crustaceans, planktonic organisms, and benthic invertebrates (Gardiner & Jones, 2005). In the ornamental trade, they fetch moderate to high prices depending on rarity and coloration, and their hardy nature increases their market demand. In Pazhaverkadu, their collection contributes to fisher livelihoods, though their site fidelity and low reproductive output necessitate careful harvest regulation to avoid stock depletion (Wabnitz *et al*., 2003; Rhyne *et al*., 2012).

Wrasses (Family Labridae)

Wrasses (Family:Labridae), including *Thalassoma lunare* (MoonWrasse) and Halichoeres hortulanus (Checkerboard Wrasse), arebrightly coloured, active reef-associated fishes frequently found in coral patches and rocky substrates near Pazhaverkadu. Some species are known to bury themselves in the sand during Night; some species are known to be cleaners of ectoparasites of other fishes. In the Minicoy, These fishes feed on crabs, alphids, fish larvae, Fish and mysids. The labrids are also known to be feeders of zooplankton and a great variety Of invertebrates including coral polyps. They playan important ecological role as cleaners, removing ectoparasites from other fish species, and are opportunistic feeders, consuming molluscs, crustaceans, worms, and occasionally small fish (Westneat & Alfaro, 2005). Wrasses are in high demand in the ornamental fish market due to their vivid colours, dynamic swimming behaviour, and adaptability in captivity, with certain species fetching premium prices in export markets. In Pazhaverkadu, they are collected selectively for the live aquarium trade, offering significant income potential but requiring sustainable practices to preserve population health and reef ecosystem stability (Wabnitz *et al*., 2003; Rhyne *et al*., 2012).

Gobies (Family Gobiidae)

Gobies are one of the largest fish families, with over 2,000 species worldwide (Nelson *et al*., 2016). They are typically small, bottom-dwelling fishes found intropical and subtropical shallow waters.Some species such as *Valenciennea strigata* (Golden-headed Sleeper Goby) and *Amblygobius phalaena* (Banded Sleeper Goby), are small benthic marine ornamental fishes widely distributed in sandy bottoms, seagrass meadows, and shallow reef-associated habitats of the Pazhaverkadu region.Known for their burrow-dwelling behaviour and symbiotic associations with certain shrimp species, gobies contribute to sediment turnover and habitat aeration. Their feeding habit primarily involves sifting sand to extract benthic invertebrates, small crustaceans, and detritus, along with consuming microalgae (Depczynski & Bellwood, 2003). In Pazhaverkadu, gobies are seasonally abundant, particularly during post-monsoon months when water clarity improves and benthic productivity is high. They hold moderate commercial value in the ornamental fish trade due to their hardy nature.

Trade and Conservation Issues

The marine ornamental fish trade in the Pazhaverkadu (Pulicat) region provides valuable income to local fishers but faces sustainability challenges due to unregulated harvesting, habitat degradation, and overexploitation of vulnerable species like seahorses and coral-dependent butterflyfishes.

Balancing economic benefits with conservation requires regulated collection, habitat protection, and promotion of captive breeding, ensuring long-term resource availability while preserving the region's biodiversity.

Conclusion

The Pazhaverkadu (Pulicat) region represents a biologically rich and economically significant hub for marine ornamental fishes, supporting a diverse assemblage of species such as clownfish, angelfish, butterflyfish, seahorses, gobies, wrasses, blennies, and cardinalfishes. These species not only contribute to the ecological stability of the estuarine and nearshore marine habitats but also sustain the livelihoods of local fishing communities through domestic and export-oriented aquarium trade. However, the growing market demand, coupled with habitat degradation and unsustainable collection practices, poses a tangible threat to the long-term viability of these resources. Species with specialized feeding habits, low reproductive rates, or habitat dependency are particularly vulnerable to overexploitation. Addressing these challenges requires a multi-pronged approach integrating science-based resource management, seasonal harvest regulation, gear restrictions, habitat restoration, and the promotion of captive breeding programs. Community engagement, combined with effective enforcement of trade regulations and international conservation agreements such as CITES, can help strike a balance between economic gain and biodiversity protection. By aligning conservation priorities with socio-economic needs, the Pazhaverkadu ornamental fishery can evolve into a sustainable model that safeguards both livelihoods and marine biodiversity for future generations.

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PLANT PROTECTION MEASURES TO BE TAKEN IN FRUIT CROPS FOR CONTINUOUS RAINS

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1. Drainage management

- Drain out excess water as soon as possible within 48 hours.
- It is suggested to take care of proper drainage facility with raised beds around the tree trunks to avoid water logging conditions.
- Remove silt/debris from existing channels, ditches or trenches.
- Make circular or V-shaped trenches around trees for quick drainage.

2. Soil management

- Mulch the tree basins with dry leaves, paddy straw, polythene sheets to reduce excess soil moisture fluctuations.
- Loosen the soil to improve aeration.
- Replant crops if damaged beyond recovery, considering soil moisture and weather forecasts.

3. Nutrient management

- After the rain ceases spray 1% KNO 3 or Urea 2% solution for 2-3 times to compensate nutrient losses due to leaching. Application of ammonical form of fertilizers is beneficial.
- The fertilizer application as per the recommendations can be applied during the end of rains to avoid leaching loss and avoid basal fertilizer application until soil becomes optimum dry.

4. Insect pest & disease management

- Keep close surveillance on disease and pest outbreak.
- Pruning of Mango leaf Webber infested shoots and burnt them away from field and later the affected trees should be sprayed with Lambda Cyhalothrin @ 2 ml/L.
- Anthracnose disease that spreads due to continuous rainfall can be controlled by the
- application of Carbendazim @ 1 g /L + Mancozeb @ 2 g/L in Mango and Guava
- Heavy rainfall causes wilt in Guava which can be controlled by the application of 30 kg mixture of (90 kg FYM + 10 kg Neem Cake + 2 kg *Trichoderma viridae*) per tree.
- Spray with COC @ 3 g /L for 3 times in 10 days interval.
- Install pheromone traps @ 4-5 per acre in guava and custard apple orchards to reduce fruit fly incidence.

5. Orchard management

- Provide staking/support with bamboo sticks to individual young plants to prevent lodging.
- Wind damaged/broken/twisted branches and water shoos should be pruned using disinfected secateurs and cut ends should be pasted with Blitox / Bordeaux paste.
- Maintain orchard sanitation by removing fallen fruits/leaves.
- Use row covers or tarps plants to protect orchards from heavy rain, hail, and strong winds.

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OPTIMIZING AGRICULTURAL PRODUCE QUALITY: PRE-HARVEST AND POST-HARVEST MANAGEMENT STRATEGIES

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Abstract
This newsletter explores comprehensive strategies for optimizing the quality of agricultural produce through integrated pre-harvest and post-harvest practices. The pre-harvest phase involves crucial decisions such as crop selection, soil management, irrigation scheduling, and pest control, all of which influence produce quality. Meanwhile, post-harvest handling, including harvesting techniques, sorting, storage, and transportation, plays a pivotal role in preserving freshness and extending shelf life. Together, these practices not only enhance food safety and nutritional value but also minimize losses and increase farmers' profitability. This article presents a comprehensive view of quality optimization strategies, emphasizing the importance of synergy between the two phases in meeting modern market demands.

Keywords : Crop management, Quality, Harvesting, Storage, Transportation

Introduction

The global agricultural sector faces a dual challenge: increasing food production to meet the growing population's needs while also enhancing the quality and safety of the produce. With the global population expected to surpass 9 billion by 2050, food security depends not only on higher yields but also on producing food that is safe, nutritious, and consumer-friendly (FAO, 2020; Idier *et al.*, 2024).

While advances in genetics, irrigation, and mechanization have boosted productivity, there is a growing emphasis on maintaining the quality, appearance, taste, nutrition, and safety of produce alongside quantity (Kader, 2002; Marotta, 2024). Quality produce improves health outcomes, meets market demands, builds consumer trust, and reduces post-harvest losses, which can reach 30–40% in developing regions (Parfitt *et al.*, 2010; Anusha *et al.*, 2024). It's also vital for meeting international trade and safety standards (Kitinoja & Kader, 2015).

Quality assurance spans from pre-harvest decisions like crop selection, soil care, and pest management to post-harvest handling, packaging, and cold chain logistics (FAO, 2020; Singh & Pal, 2008). Precision agriculture and digital monitoring further enhance this process, helping farmers produce higher-quality food sustainably (Business Insider, 2025; Mehdipour *et al.*, 2025).

This newsletter examines how integrating these strategies boosts profitability, supports environmental goals, enhances nutrition security, and builds resilience to climate change (FAO, 2020; Anusha *et al.*, 2024; Marotta, 2024).

Pre-Harvest Management Strategies

Crop Selection and Soil Health

Choosing the right crop variety adapted to local agro-climatic conditions is foundational to quality outcomes. Factors such as temperature tolerance, rainfall pattern compatibility, disease and pest resistance, and anticipated market demand should guide varietal selection. For example, drought-tolerant cultivars can ensure quality under erratic rainfall conditions (FAO, 2020). Equally important is soil health, which affects plant nutrient uptake and resistance to stress. Techniques such as incorporating compost and green manure can enhance organic matter content. Soil pH should be monitored and adjusted using lime or sulphur to optimize nutrient availability. Practices like crop rotation and cover cropping help maintain soil structure and microbial diversity, both of which are linked to improved produce quality and resilience (Kader, 2002; FAO, 2020).

Irrigation and Nutrient Management

Proper irrigation scheduling avoids plant stress that may reduce both yield and the organoleptic quality of produce. Under-irrigation may lead to stunted growth and poor fruit development, while over-irrigation increases disease susceptibility and nutrient leaching (Kader, 2002).

Nutrient management should be based on regular soil and tissue analysis to provide balanced fertilization. Both macro- and micronutrients influence the physical and nutritional characteristics of produce. For example, adequate potassium enhances fruit color and shelf life, while calcium reduces post-harvest physiological disorders like blossom end rot (Kader, 2002; FAO, 2020).

Pest and Disease Control

Integrated Pest Management (IPM) strategies reduce reliance on chemical pesticides, thus lowering the risk of residues in food and promoting environmental sustainability. Biological control agents, such as *Trichoderma* fungi or predatory insects, are increasingly used to suppress pests without compromising food safety (FAO, 2020).In addition, regular field scouting and threshold-based pesticide application minimize unnecessary treatments. Cultural controls, such as crop rotation, sanitation, and resistant varieties, are equally crucial in maintaining the health and marketability of crops (FAO, 2020; Kader, 2002).

Post-Harvest Management Strategies

Harvesting Techniques

Timing is critical in harvesting; produce harvested too early may lack flavor and nutritional maturity, while late harvesting can result in over-ripeness and spoilage. For example, harvesting tomatoes at the breaker stage improves their transport durability without compromising eventual ripening (Kitinoja & Kader, 2015). Proper tools, such as sharp knives or scissors, and trained labor reduce mechanical injuries like bruises and cuts that can initiate microbial decay. Furthermore, harvesting during cooler parts of the day helps preserve post-harvest quality by reducing field heat, which accelerates deterioration (Kader, 2002; Kitinoja & Kader, 2015).

Sorting, Grading, and Packaging

Sorting eliminates damaged or diseased produce that could contaminate others during storage or transit. Grading by size, color, and ripeness ensures uniformity, which is a key quality criterion in markets and retail (Kader, 2002). Packaging not only protects produce from physical damage but also regulates moisture and gas exchange. Modern innovations include modified atmosphere packaging (MAP) and the use of biodegradable or recyclable materials, aligning with sustainability goals (Kitinoja & Kader, 2015). Proper labeling during packaging also supports traceability, which is critical in today's food safety landscape (FAO, 2020).

Storage and Transportation

Post-harvest quality can deteriorate rapidly if storage conditions are suboptimal. Temperature control slows respiration and microbial activity; for instance, leafy greens typically require storage at 0–1°C to retain crispness and nutrients (Singh & Pal, 2008). Humidity control prevents desiccation or excess moisture that fosters mold growth. Cold chain logistics from farm storage to retail delivery are essential for perishable goods. Even short breaks in the cold chain can significantly reduce shelf life. Transportation should be done in padded containers or crates to avoid impact damage, and refrigerated trucks should maintain target temperatures throughout the journey (Parfitt *et al*., 2010).

Conclusion

Optimizing the quality of agricultural produce requires an integrated approach that spans both pre-harvest and post-harvest stages. Pre-harvest management ensures that crops grow under optimal environmental and nutritional conditions, with minimal pest and disease stress. Post-harvest practices maintain and protect this quality until the product reaches consumers. Together, these strategies improve food safety, enhance market value, reduce losses, and increase profitability for farmers. Future efforts should focus on farmer training programs, infrastructure development for cold storage and logistics, and adopting precision agriculture technologies such as drones and IoT sensors to monitor crop and environmental parameters in real time (FAO, 2020; Kitinoja & Kader, 2015; Kader, 2002).

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FROM LAB TO POND: HOW CRYOPRESERVATION SUPPORTS AQUACULTURE INNOVATION

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Abstract
Cryopreservation enables long-term storage of fish gametes and tissues, supporting aquaculture by preserving genetic resources and enhancing breeding programs. Freezing water in cells can cause damage via ice formation or solute concentration, but cryoprotectants like DMSO, glycerol, and methanol mitigate these effects. Proper cooling, thawing, and membrane permeability management are critical to maximize survival. Techniques such as vitrification avoid ice formation but require careful control of cryoprotectant toxicity. By bridging laboratory research and practical aquaculture, cryopreservation facilitates year-round breeding, hybridization, and germplasm conservation, driving innovation in fish production and genetic management.

Keywords: Aquaculture, Cryopreservation, Cryoprotectants, Gamete Preservation, Hybridization

Introduction

Aquaculture has emerged as one of the fastest-growing sectors in global food production, offering sustainable solutions to meet the rising demand for fish and other aquatic products. As the industry expands, maintaining high-quality brood stock, conserving genetic diversity, and ensuring year-round availability of superior seeds have become critical priorities (Mohd *et al.*, 2025).Cryopreservation, often described as “preserving life on ice,” has provided aquaculture with a powerful tool to address these challenges. By storing gametes, embryos, and even somatic cells at ultra-low temperatures, cryopreservation allows biological material to remain viable for extended periods without loss of functionality (Wrigley, 2021). The application of cryopreservation in aquaculture spans several dimensions (Fig. 1).It enables selective breeding programs by ensuring a reliable supply of gametes, thus enhancing genetic improvement in farmed species.It also plays a vital role in conserving endangered or overexploited aquatic species, safeguarding biodiversity for future generations. Furthermore, cryopreserved germplasm facilitates international exchange of genetic resources without the risk of spreading diseases associated with live animal transport (Engdawork *et al.*, 2024). In commercial settings, hatcheries benefit from cryobanks by ensuring consistent seed supply regardless of seasonal or biological limitations Advances in cryobiology and reproductive biotechnology continue to refine methods for sperm, oocyte, and embryo cryopreservation in finfish, shellfish, and ornamental species. While challenges remain particularly in the cryopreservation of fish embryos due to their large size and high yolk content ongoing research holds promise for overcoming these barriers. The integration of nanotechnology, improved cryoprotectants, and precision cooling techniques is expected to revolutionize the field further (Wang *et al.*, 2024). In essence, cryopreservation bridges the gap between laboratory innovation and practical aquaculture development. It supports food security, genetic conservation, and economic sustainability, making it a cornerstone technology in shaping the future of fisheries and aquaculture. From lab to pond, cryopreservation is redefining how aquatic resources are preserved, managed, and utilized.

Cryopreservation

Fish breeding is influenced by numerous factors, and even successful hatcheries often experience partial or complete failures in spawning. To ensure adequate seed production, induced breeding is widely used, enabling fish to mature and spawn despite low rainfall or adverse climatic conditions (Sun *et al*., 2025). However, repeated breeding attempts can compromise the health of brooders, and exchanging brooders is challenging due to transportation difficulties and physiological constraints. An effective alternative is the shipment of gametes, which circumvents these limitations and mirrors practices in animal husbandry. Incorporating biotechnological tools into breeding programs is essential for sustainable seed production. Cryopreservation offers a reliable solution, allowing long-term storage of gametes without significantly reducing their fertilization capacity. By cooling gametes to approximately −196 °C, all biological activity including biochemical reactions that lead to cell death and DNA degradation is halted, preserving their viability for years (Cimini *et al*., 2025). The FAO recognizes cryopreservation as a crucial strategy for conserving fish genetic resources and supporting the development of genetically improved varieties.

Principle of Cryopreservation

The fundamental principle of cryopreservation is the exposure of living cells to ultra-low temperatures, typically around −196 °C, to arrest biological activity without compromising cell viability (Cimini *et al*., 2025). The process involves complex heat and water transport dynamics between cells and their surrounding medium during freezing and thawing. The outcome largely depends on the rate of cooling or thawing. When cells in an aqueous solution are cooled slowly, both the cells and the surrounding solution become supercooled, leading to extracellular ice formation (Xiong *et al*., 2025; Yadav *et al*., 2025). Water gradually leaves the cells to maintain osmotic balance, but excessive dehydration can result in cell death, known as freeze-killing. In contrast, rapid cooling minimizes water loss and prevents intracellular ice formation, a process called vitrification, which preserves cell integrity. During thawing, cellular processes occur in reverse. To avoid lethal ice recrystallization, rapid warming is necessary, ensuring dehydrated cells do not reabsorb water too quickly, thereby maximizing post-thaw survival.

Cryopreservation Procedure

Sample Collection : The first step involves collecting the biological material, such as fish sperm, eggs, or embryos, under sterile and controlled conditions to ensure sample quality and prevent contamination.

Preparation of CPA (Cryoprotective Agent) : Cryoprotective agents are prepared to protect cells from ice crystal formation and osmotic damage during freezing. Common CPAs include DMSO, glycerol, and methanol, which penetrate cells or act extracellularly to stabilize them.

Sample Processing : The collected samples are mixed with the CPA carefully, allowing proper equilibration. This step ensures that cells are adequately protected during the freezing process.

Controlled Cooling : Samples are cooled gradually at a predetermined rate to avoid intracellular ice formation and osmotic shock. Controlled cooling helps maintain cell integrity.

Vitrification (if applicable) : In some cases, rapid cooling or vitrification is employed to solidify the sample into a glass-like state without ice crystal formation, enhancing survival.

Storage : Samples are stored in ultra-low temperature conditions, typically in liquid nitrogen at −196°C, to preserve them for long-term use.

Thawing : Samples are thawed rapidly to minimize ice recrystallization, which can damage cells. The thawing rate is usually matched with the cooling rate for optimal recovery.

Recovery & Assessment : Finally, thawed samples are assessed for viability, fertilization potential, and overall quality before being used in breeding programs.

Applications of Cryopreservation in Aquaculture

Preservation of quality milt : Best-age brooder sperm can be stored and used anytime in the future.

Prevention of inbreeding : Cryopreserved sperm can be easily exchanged between hatcheries.

Year-round availability : Spermatozoa can be stored and used irrespective of breeding season.

Off-season breeding : Enables reproduction even outside the natural breeding period.

Gamete synchronization: Aligns availability of eggs and sperm, promoting efficient use of gametes.

Simplified brood stock management: Reduces the need to maintain large breeding populations year-round.

Enhanced offspring quality: Supports intra-species hybridization to produce viable and strong progeny.

Extended gamete viability: Overcomes limitations due to the short lifespan of fresh gametes.

Genetic preservation: Maintains desired lines for selective breeding or conservation.

Crossbreeding flexibility: Facilitates hybridization at different times of the year.

Germplasm storage: Supports genetic selection programs and species conservation.

Support for research: Cryopreserved sperm aids hybridization programs and genetic engineering in fish.

Cryobanking potential : Opens avenues for gene banks, genetic manipulation, and long-term preservation of valuable fish germplasm.

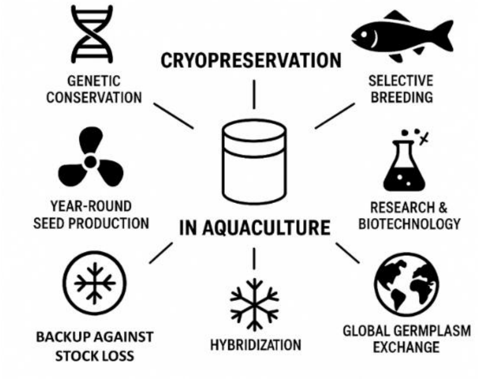

Fig. 1 Different applications of cryopreservation in aquaculture

Cryoprotectants

Cryoprotectants are low molecular weight compounds that penetrate cells and lower the freezing point of solutions, protecting spermatozoa during cryopreservation. They require time to penetrate cells (equilibration), but prolonged exposure can be toxic. High concentrations reduce cryoinjuries but may also become harmful, so optimal concentration is crucial. The effectiveness of cryoprotectants varies among fish species.

There are two main types:

1. **Permeating cryoprotectants :** Small molecules like DMSO, glycerol, methanol, and propanediol that enter cells, replace water, lower the freezing point, minimize osmotic shock, and reduce intracellular ice formation.
2. **Non-permeating cryoprotectants :** Larger molecules or compounds like milk proteins, egg yolk, BSA, sugars (glucose, sucrose), and synthetic polymers (PEG, PVP) that stabilize the cell membrane during freezing.

Insufficient cryoprotectant reduces effectiveness, while excessive amounts can cause osmotic swelling or rupture during thawing. Cryoprotectants prevent ice crystal formation and delay intracellular freezing, minimizing cellular damage.

Common examples in fish sperm cryopreservation:

- **DMSO :** Effective in many freshwater species; considered a universal cryoprotectant.
- **Methanol :** Suitable for bitterling, bagrid catfish, tilapia, and *C. gariepinus*.
- **Propylene glycol (PG) :** Effective for yellowtail flounder; moderate results in *C. gariepinus.*
- **Combinations :** Using glucose or egg yolk with cryoprotectants can enhance post-thaw motility, as shown in *C. mrigala* and *C. carpio* (Siva, 2021).

Fish Egg and Embryo Cryopreservation: Current Status and Future Directions

Cryopreservation of fish eggs and embryos is still in its experimental stage, unlike the well-established cryopreservation of sperm. Only a few attempts have been made to preserve eggs and embryos of species such as rainbow trout (*Oncorhynchus mykiss*), Japanese medaka (*Oryziaslatipes*), zebrafish (*Brachydanio rerio*), rohu (*Labeorohita*), and common carp (*Cyprinus carpio*) (Siva, 2021). Most efforts have faced challenges due to the large size of eggs and embryos, high yolk content, and the presence of multi-layered membranes, which reduce water and cryoprotectant permeability and make uniform cooling and warming difficult. Eggs and embryos are also highly sensitive to low temperatures, which often leads to ice formation and cellular damage. Researchers have explored strategies such as microinjection of cryoprotectants or antifreeze proteins into the cytoplasm, application of negative or hydrostatic pressure to improve permeability, and the selection of effective cryoprotectants. For example, methanol penetrates zebrafish embryos quickly and efficiently, whereas DMSO and propylene glycol show limited penetration. Despite these advances, survival rates remain low, emphasizing the need for further research to develop reliable protocols for egg and embryo cryopreservation.

Conclusion

Cryopreservation has been developed for many fish species, but species-specific protocols are still needed to ensure high success rates in artificial fertilization programs. Even with standard procedures, cryoinjuries are inevitable, so optimizing freeze–thaw cycles and addressing oxidative stress are essential. The impacts of cryopreservation on sperm energy production, reactive oxygen species (ROS) generation, mitochondrial DNA, and sperm structure must be thoroughly studied. Unlike in livestock, few fish sperm banks exist, especially in developing countries. Addressing these research gaps is crucial to establish effective fish sperm banks for commercially important species and to fully realize the potential of cryopreservation in aquaculture.

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REAL-TIME CROP INTELLIGENCE: THE ROLE OF NANOSENSORS IN AGRICULTURE

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Abstract

Nanotechnology has emerged as a transformative tool in modern agriculture, with nanosensors offering unprecedented opportunities for real-time monitoring and precision management of crops, soil, and the environment. Owing to their unique physicochemical properties, nanosensors exhibit high sensitivity and specificity in detecting nutrients, pathogens, toxins, and environmental parameters. They facilitate optimized input use, early disease diagnosis, and improved food quality assessment. This chapter explores the principles, types, applications, benefits, and limitations of nanosensors in agriculture, while also highlighting future prospects for integrating nanosensors with smart farming and digital agriculture systems.

Key words: nano sensors, precision farming, current agriculture, plant health monitoring

Introduction

Agriculture, the backbone of global food security, is facing unprecedented challenges due to climate variability, soil degradation, water scarcity, pest outbreaks, and the growing demand for safe and nutritious food. Traditional farming practices often rely on generalized input application and reactive responses to stress, which result in resource inefficiency, yield gaps, and environmental pollution. In this context, nanotechnology has emerged as a transformative science offering innovative tools for modern agriculture. Among its applications, nanosensors have gained significant attention as highly sensitive devices capable of detecting chemical, physical, and biological changes at the molecular level.Nanosensors, developed using materials such as carbon nanotubes, graphene, metal nanoparticles, and quantum dots, provide real-time, site-specific, and ultra-precise information about soil health, crop physiology, water quality, and environmental conditions. Their ability to sense stress factors, pathogens, and nutrient imbalances before visible symptoms occur allows farmers to adopt preventive and precision-based management practices. This is particularly important in India and other developing countries, where smallholder farmers depend heavily on timely information for crop survival and income security.The importance of nanosensors in current agriculture lies in their capacity to integrate with smart farming technologies such as the Internet of Things (IoT), drones, and artificial intelligence. Together, these systems enable precision agriculture, where inputs like water, fertilizers, and pesticides are optimized based on accurate, localized data. This not only improves productivity and profitability but also minimizes the overuse of agrochemicals, thus reducing costs and environmental risk.

Key Applications of Nanosensors in Agriculture

i. Smart Farming and Precision Agriculture

Nanosensors are central to the advancement of precision farming by enabling real-time, data-driven decision-making. They provide accurate information on soil moisture, nutrient availability, and environmental conditions, thereby supporting site-specific input application. This not only enhances productivity but also conserves resources such as water and fertilizers, aligning with the principles of sustainable agriculture (Prasad et al., 2017; Chen et al., 2021).

ii. Plant Health Monitoring

- **Stress Detection:** Embedded nanosensors can detect physiological stress in plants caused by drought, salinity, or pathogen attack before visible symptoms occur. This early warning system enables farmers to take preventive action, reducing yield losses (Dasgupta & Ranjan, 2017).
- **Nutrient Management:** Nanosensors can monitor macro- and micronutrient concentrations in soil and within plant tissues. By guiding precise fertilizer application, they reduce nutrient leaching, minimize environmental contamination, and improve nutrient use efficiency (Singh & Mishra, 2020).

iii. Pest and Disease Management

- **Early Detection:** Nano-biosensors can identify volatile organic compounds or molecular markers released during pest or pathogen invasion, allowing timely intervention with minimal pesticide use (Sekhon, 2014).
- **Pheromone Detection:** Nanosensors have also been developed to detect insect pheromones, offering innovative, non-invasive tools for monitoring insect populations and integrating with eco-friendly pest management strategies (Prasad et al., 2017).

iv. Environmental Monitoring

Nanosensors facilitate comprehensive monitoring of agro-ecosystems by detecting parameters such as soil pH, organic matter, temperature, and humidity. Such data provides insights into the microenvironment influencing crop growth and supports adaptive management under climate variability (Chen et al., 2021; Sekhon, 2014).

Types of Nanosensors in Agriculture

i. **Chemical Nanosensors**
   - Detect soil nutrients, pesticides, or pollutants using nanomaterials with high reactivity.
   - Example: Carbon nanotube-based nitrate sensors.

ii. **Physical Nanosensors**
   - Measure environmental parameters like soil moisture, temperature, or pressure.
   - Example: Nano-hydrogel–based water sensors.

iii. **Biosensors (Nano-biosensors)**
   - Use biological recognition elements (enzymes, DNA, antibodies) with nanomaterials to detect pathogens or toxins.
   - Example: Gold nanoparticle-based biosensors for rice blast detection.

iv. **Optical Nanosensors**
   - Employ quantum dots or fluorescent nanoparticles to detect changes in plant tissues or soil.
   - Example: Fluorescent nanosensors for detecting heavy metals in irrigation water.

v. **Electrochemical Nanosensors**
   - Measure electrical signals generated by biochemical reactions.

- Example: Electrochemical nanosensors for urea concentration monitoring.

Advantages of Nanosensors in Agriculture

i. **High Sensitivity and Precision:** Detect changes at molecular levels.
ii. **Real-time Monitoring:** Provides instant data for decision-making.
iii. **Reduced Input Costs:** Optimizes fertilizer, water, and pesticide usage.
iv. **Enhanced Food Safety:** Monitors contaminants and quality in supply chains.
v. **Supports Precision Agriculture:** Enables site-specific and data-driven farming.

Limitations of Nanosensors

i. **High Cost of Development and Deployment** in smallholder farming systems.
ii. **Environmental Concerns** regarding persistence and toxicity of engineered nanomaterials.
iii. **Lack of Standardization** in field testing and large-scale applications.
iv. **Need for Technical Training** among farmers and extension workers.
v. **Regulatory Challenges** related to biosafety and consumer acceptance.

Conclusion

Nanosensors represent a breakthrough in agricultural monitoring systems by enabling precise, real-time, and site-specific management of crops and resources. Their application spans soil fertility, plant health, irrigation efficiency, food quality, and environmental sustainability. However, widespread adoption requires addressing challenges such as affordability, standardization, safety concerns, and farmer training. Future advancements in biodegradable nanomaterials, integration with the Internet of Things (IoT), and data-driven decision support systems hold promise for making nanosensors a cornerstone of smart and sustainable agriculture.

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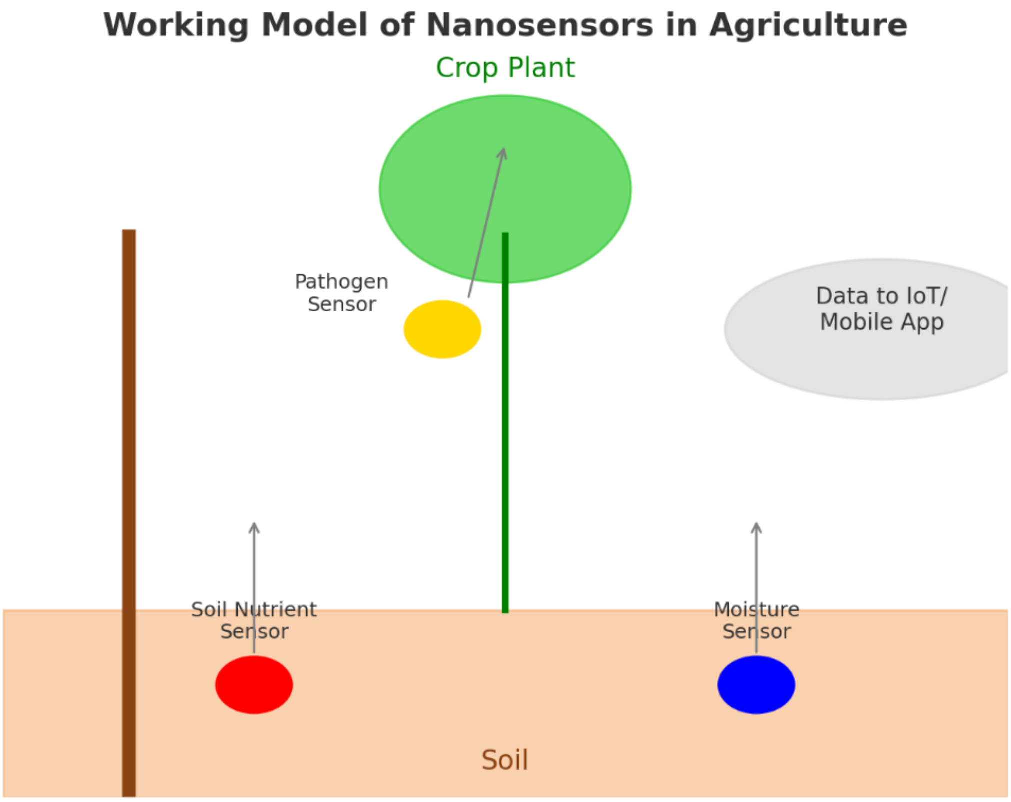

Fig: diagram of nanosensors in agriculture showing how soil nutrient, moisture, and pathogen sensors collect data and transmit it to IoT/mobile applications for precision farming.

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INDIA'S BLUE REVOLUTION 2.0: A DEEP DIVE INTO FISHERIES INNOVATION AND DEEP-SEA EXPLORATION

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Abstract

India's fisheries sector is undergoing a strategic transformation. With mounting pressure on coastal stocks, rising demand for seafood, and climate-induced shifts in marine ecosystems, the country is now looking to its vast Exclusive Economic Zone (EEZ) for sustainable growth. The government's renewed focus on deep-sea exploration, technological modernization, and science-led management reflects an ambitious plan to reshape the sector through innovation and inclusion. This article explores the key developments in India's marine strategy, from mesopelagic resource mapping and digital governance to climate-resilient aquaculture and policy reform.

Introduction

For decades, India's fisheries sector has been dominated by nearshore activities and small-scale fishers. While this approach has supported livelihoods and food security, it has also led to overexploitation of coastal waters and a stagnation in productivity. Today, with nearly 4 million tonnes of marine capture production annually and increasing international seafood demand, India is aiming to expand beyond the shallows.

In response, the government has set its sights on deeper waters, leveraging marine science and technology to tap underutilized resources. The goal is not just economic gain—but also sustainability, equity, and resilience in a changing ocean landscape.

Exploring the Deep: Tapping India's Mesopelagic Zone

In early 2025, two leading research institutes—CMFRI and CIFT—launched a collaborative pilot project to explore India's mesopelagic zone (200–1000 meters deep). This twilight region of the ocean, rich in lanternfish and myctophids, is thought to hold significant industrial potential. The goal of the study is to assess stock density, ecosystem role, and harvest feasibility without disrupting deep-sea biodiversity.

These efforts align with India's broader **Blue Economy Vision**, which promotes responsible use of ocean resources while ensuring long-term ecological balance. The findings from this pilot, expected by 2026, could set the foundation for large-scale deep-sea fisheries development with international best practices.

Policy Momentum: Budget Boosts and National Missions

India's intent to scale its marine resources is backed by robust policy and funding support. The Union Budget 2025 allocated ₹2,700 crore under the Pradhan Mantri Matsya Sampada Yojana (PMMSY)—marking one of the largest investments in the sector to date.

Additionally, India's Deep Ocean Mission, spearheaded by the Ministry of Earth Sciences, is pushing the envelope with technology such as Matsya 6000, a human-rated submersible capable of descending to 6,000 meters. While primarily aimed at oceanographic research and mining, this mission also supports marine biodiversity studies and advanced fisheries mapping.

These efforts reflect a dual approach: harnessing scientific potential while strengthening institutions and livelihoods along India's 8,000 km coastline.

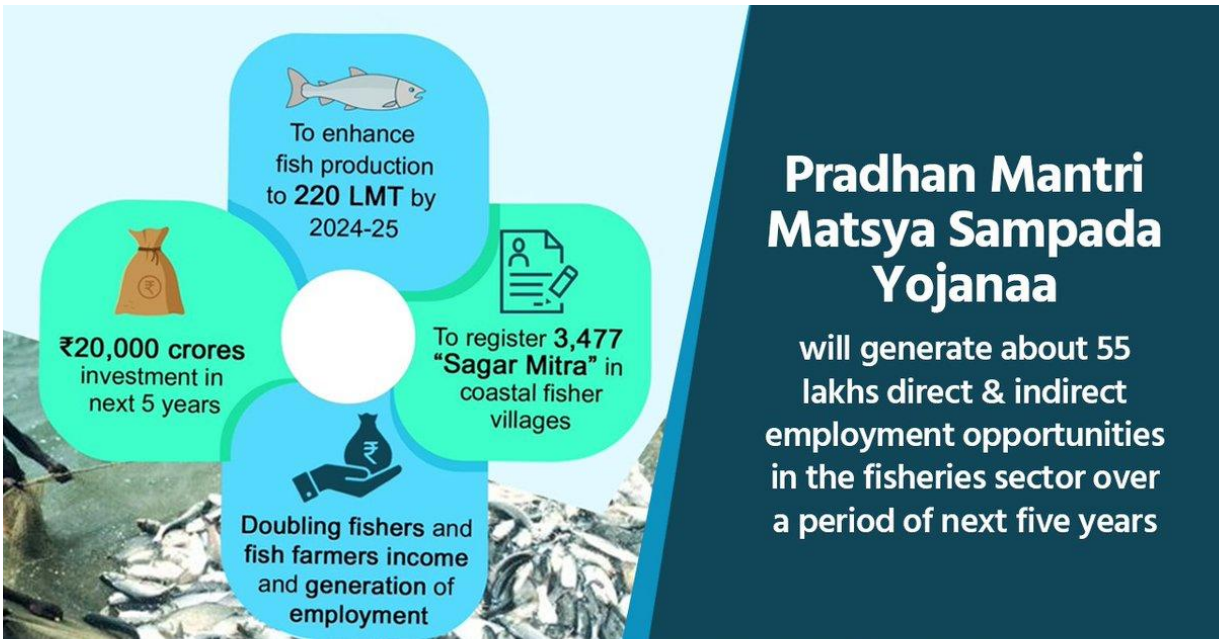

Figure 1: Pradhan Mantri Matsya Sampada Yojanaa

Digital Transformation and Fisheries Governance

One of the most revolutionary changes in Indian fisheries is happening onshore—through data. In 2025, CMFRI launched the Fifth Marine Fisheries Census, covering over 1 million households using geospatial tools and mobile applications.

Real-time data collected through the VyAS-NAV app is shaping new fisheries management plans, supporting seasonal forecasting, and helping local governments allocate subsidies, insurance, and gear more efficiently.

Furthermore, platforms under PM Matsya Sampada now provide digital access to credit, cold storage, and value-chain support—particularly benefiting marginalized groups such as SC/ST fishers and women's cooperatives.

This data-driven governance model is key to building adaptive and inclusive fisheries for the future.

Aquaculture Innovation: From Shore to Offshore

With wild catch plateauing, India is rapidly expanding its aquaculture base. Advanced farming systems such as Recirculating Aquaculture Systems (RAS), biofloc units, and offshore cage farming are being promoted for species like seabass, cobia, and shrimp.These technologies allow for high-density, low-impact farming, reducing dependency on land and freshwater. In parallel, seaweed and shellfish farming is being scaled up in states like Tamil Nadu, Odisha, and Gujarat to diversify income and support climate mitigation.

Through PMMSY and other schemes, over 2,000 Fish Farmers Producer Organizations (FFPOs) have been formed to consolidate smallholder production and enhance export readiness.

Challenges in India's Fisheries Innovation & Deep-Sea Exploration

Category	Challenge	Explanation
Ecological	Deep-sea ecosystem sensitivity	Mesopelagic and bathypelagic zones are poorly understood; extraction could disrupt food chains.
	Bycatch and species loss	Deep-sea fishing often results in unintended catch, including endangered or juvenile species.
	Climate change impacts	Rising temperatures, ocean acidification, and coral bleaching affect marine biodiversity and fish stock.
Technological	Limited access to deep-sea vessels	Most traditional fishers lack advanced boats and tools for deep-sea fishing.
	Insufficient real-time monitoring tools	Lack of widespread use of satellite tracking, AI stock prediction, and smart gear.
Socioeconomic	Exclusion of small-scale fishers	Technological shift may marginalize low-income coastal communities.
	Skill and training gaps	Need for capacity building in deep-sea operations, aquaculture management, and digital tools.
	Financial barriers	High cost of modern gear, inputs, and insurance remains a hurdle for many.
Regulatory & Policy	Weak enforcement of marine regulations	Monitoring of India's vast EEZ is limited; IUU (illegal, unreported, unregulated) fishing remains a risk.
	Fragmented policy coordination	Multiple agencies with overlapping jurisdictions lead to gaps in planning and implementation.
	Slow implementation of conservation laws	Although laws exist (e.g., Wildlife Act), their on-ground execution is inconsistent.

Conclusion

India's current fisheries roadmap reflects a thoughtful convergence of science, technology, and policy. From the mapping of mesopelagic zones to the digitization of marine governance, the country is moving toward a modern and resilient fisheries economy.

What sets this transformation apart is its ambition to align environmental sustainability with inclusive development. If implemented effectively, India's Blue Revolution 2.0 could not only secure marine biodiversity and improve food security, but also empower millions of coastal families.

As the deep sea becomes the new frontier, India's challenge will be to tread carefully—balancing innovation with conservation, and growth with equity.

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THE ROLE OF N-3 PUFAS AND CLA IN ENRICHED MEAT AND EGGS

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Abstract

n-3 polyunsaturated fatty acids (PUFAs) and conjugated linoleic acid (CLA) are bioactive lipids with significant health-promoting properties. This review explores their dietary sources, mechanisms of action, and strategies to enrich meat and eggs through feed supplementation and improved rearing systems. Enriched products show enhanced fatty acid profiles and health benefits, including cardiovascular protection, anti-inflammatory activity, and improved metabolic functions. However, enrichment may also impact sensory attributes and oxidative stability. Bioavailability varies based on form and dietary matrix, while synergistic effects with antioxidants and gut microbiota may influence efficacy. Balanced omega-6: omega-3 ratios and isomer-specific research are vital for maximizing functional value in enriched animal products.

Keywords: n-3 PUFAs; Conjugated linoleic acid; Functional foods; Enriched meat; Enriched eggs; Omega-3 fatty acids; CLA isomers; Lipid bioavailability; Antioxidants; Fatty acid metabolism.

Introduction

Bioactive lipids like omega-3 polyunsaturated fatty acids (n-3 PUFAs) and conjugated linoleic acid (CLA) are essential for human health. n-3 PUFAs, including ALA, EPA, and DHA, play roles in reducing inflammation, improving heart and brain function, and regulating lipid metabolism. Since humans lack the enzymes to synthesize ALA, it must be obtained through diet. EPA and DHA are mainly found in fatty fish, while ALA comes from flaxseed, walnuts, and green vegetables. CLA, primarily found in ruminant fats such as milk and beef, consists mainly of the c9, t11 isomer (rumenic acid) and the t10, c12 isomer. These isomers have different physiological effects: c9, t11 is anti-inflammatory, while t10, c12 is anti-obesity. n-3 PUFAs and CLA act through gene regulation mechanisms like PPARs and NF-κB, influencing fat metabolism, immune function, and disease prevention. However, the conversion of ALA to EPA/DHA is limited (<15%), and high intake of n-6 PUFAs can hinder this process. Therefore, direct intake of EPA/DHA and a balanced n-6:n-3 ratio are vital for optimal health outcomes.

Strategies for Nutritional Enrichment of Meat and Eggs

Enhancing n-3 PUFA Content

Dietary Supplementation

Feeding flaxseed (10–20%) to poultry increases ALA, EPA, and DHA in eggs and meat. Fish oil (1–2%) directly enhances EPA and DHA levels, with up to 500 mg DHA per egg reported. Microalgae (e.g., Schizochytrium sp.) at 0.5–1% efficiently enrich DHA without off-flavors. Due to PUFA oxidation, antioxidants like Vitamin E, selenium, and lutein are added to maintain quality. In ruminants, flaxseed raises ALA in milk and beef, and may reduce saturated fat. Fish oil increases

EPA and DHA, but rumen biohydrogenation reduces PUFA availability. Processing methods like heat-treated flaxseed help protect PUFAs.

Rearing Systems & Forage Ratios

Pasture-based systems significantly increase CLA (3–5×), ALA, EPA, DPA, and DHA in meat and milk, and improve the n-6: n-3 ratio. Higher forage: concentrate ratios (e.g., 65:35) raise n-3 PUFA and CLA, and reduce saturated fats in beef. Milk CLA content also varies with season, time, and pasture quality. Free-range poultry produce eggs and meat with higher omega-3s, vitamin A, and E, and lower n-6: n-3 ratios. Pasture-raised chicken has significantly more omega-3 than conventional poultry.

Increasing CLA Content

Ruminant CLA Synthesis

In ruminants, CLA is naturally synthesized by rumen microbes (e.g., *Butyrivibrio fibrisolvens*) and in the mammary gland from vaccenic acid via stearoyl-CoA desaturase. Manipulating forage: grain ratio, pH, and adding linoleic acid-rich oils (e.g., sunflower, linseed, soybean) enhances CLA in beef and milk.

CLA in Non-Ruminants

Poultry and pigs have low endogenous CLA; thus, direct CLA supplementation is used. Feeding 0.75% CLA increases CLA in chicken meat; 5% inclusion in hen diets can yield egg yolks with up to 11% CLA. CLA also transfers effectively to embryos in broiler breeders, altering yolk and residual fatty acid profiles.

Nutritional Profile and Quality of Enriched Products

Alterations in Fatty Acid Composition

n-3 PUFA enrichment significantly increases total omega-3s

Enriched eggs significantly improve omega-3 content, reaching up to 480.65 mg/100g of n-3 PUFA compared to 204.58 mg in conventional eggs, thereby enhancing the n-6: n-3 ratio from approximately 8.69:1 to 2.19:1. Similarly, chicken meat, particularly the liver, exhibits elevated levels of EPA and DHA with a better omega-6: omega-3 balance. In beef, grass-fed or forage-rich diets lead to higher concentrations of ALA, EPA, DPA, and DHA, while also reducing saturated fatty acids (SFAs). Pork fed with flaxseed (5–10%) demonstrates a marked increase in omega-3 fatty acids and a substantial improvement in the n-6: n-3 ratio, decreasing it by up to 12.4-fold.

CLA enrichment yields

CLA enrichment improves the fatty acid profile in animal products. In eggs, yolk CLA increases with changes in linoleic, palmitoleic, and arachidonic acids. Chicken meat shows higher CLA, especially the (t10, c12) isomer, along with reduced MUFAs and n-6 PUFAs. Grass-fed beef and oil supplementation raise CLA levels, while dietary additions similarly boost CLA in pork.

Impact on Product Quality

n-3 PUFA Enrichment

Oxidative Stability: PUFAs oxidize easily, reducing shelf life and flavor. **Antioxidants** are critical to prevent degradation.

Sensory Traits: Fish oil may cause a "fishy taste" in eggs and meat; flaxseed can darken yolks or cause off-flavors. Microalgae have fewer sensory issues. Excess n-3 in pork leads to rancidity and reduced tenderness. Some studies report **no sensory decline** in enriched beef or pork.

Shelf Life: Improved by antioxidant use, especially Vitamin E.

CLA Enrichment

Oxidative Stability: Results vary—some report reduced lipid oxidation, others increased peroxidation; effects depend on **isomer and diet**.

Sensory Traits: Roasting preserves CLA best in chicken, though redness may decrease. In pork, CLA can enhance marbling without negative sensory effects. CLA-enriched dairy retains acceptability.

Other Effects: High CLA may lower body weight, feed efficiency in poultry, or egg quality in hens. In pork, it can improve lean yield but reduce belly firmness.

Human Health Implications of Enriched Meat and Eggs

n-3 polyunsaturated fatty acids (PUFAs) improve lipid profiles by reducing triglycerides, LDL, VLDL, and chylomicron size, exhibit antiarrhythmic and vasodilatory effects, and may lower mortality in coronary heart disease and heart failure patients; enriched eggs have also been shown to reduce blood triglycerides.

Conjugated linoleic acid (CLA) may support lipid metabolism, lower blood pressure (when combined with ramipril), and reduce atherosclerosis, though human studies show mixed effects on LDL and HDL levels, with some associating high CLA intake with reduced heart failure risk in older men. Both n-3 and CLA exhibit anti-inflammatory effects—n-3 by reducing leukocyte chemotaxis and producing resolvins, and CLA via PPARγ activation and NF-κB inhibition though human data remain inconsistent. n-3 PUFAs may also improve body composition by enhancing fat oxidation, lean mass, and insulin sensitivity, while CLA has shown potential to reduce body fat and appetite, despite inconsistent effects on BMI and a possible increased diabetes risk with the (t10, c12) isomer. Additional benefits of n-3 include support for brain function, vision, and possible cancer protection, whereas CLA has demonstrated anti-cancer effects in animal models and potential to slow cancer progression in humans.

Bioavailability and Metabolism

n-3 PUFA Bioavailability

n-3 absorption is 85–95% efficient. However, ALA conversion to EPA/DHA is limited 8% to EPA and 0–4% to DHA in men, slightly higher in women due to estrogen. Direct EPA/DHA intake from fish or enriched foods is recommended. Food matrix and preparation (e.g., omelet vs. boiled egg) influence DHA absorption. DHA in eggs (as phospholipids) may be more bioavailable than fish oil (as triglycerides). Non-dietary factors like sex, genetics, age, and lifestyle also affect n-3 PUFA levels.

CLA Bioavailability

CLA is absorbed after digestion and incorporated into tissues. Lamb > beef > pork/chicken in CLA content. Supplementation can raise CLA in non-ruminants (e.g., 11% in yolk with 5% CLA in feed). Daily intake ranges from 50–500 mg. Some gut microbes (Lactobacillus, Bifidobacterium) may convert LA to CLA. Human studies show variable outcomes. CLA from enriched dairy can raise plasma CLA, but health effects are often inconclusive. CLA from egg yolk may activate PPARs more effectively than synthetic forms.

Synergistic and Antagonistic Effects

Effects on Product Stability

n-3 PUFAs are highly unsaturated and prone to oxidation, affecting shelf life and taste. Antioxidants (e.g., Vitamin E, selenium) are essential in maintaining quality. Selenomethionine + fish oil improves oxidative stability and flavor in pork. CLA's role in oxidation is unclear—some studies report reduced oxidation, others increased lipid peroxidation in chicken meat.

Effects on Human Health

n-3 and n-6 PUFAs compete for desaturase/elongase enzymes. High n-6 intake suppresses ALA → EPA/DHA conversion, increasing inflammation risk. Balanced n-6: n-3 intake is key. CLA inhibits LA elongation, reducing ARA and pro-inflammatory eicosanoids. It may boost DHA production via peroxisomal β-oxidation. Combined CLA + n-3 PUFA supplementation in rats reduced lipids and white fat while increasing brown fat and thermogenesis, though it also increased food intake. Gut probiotics (Lactobacillus, Bifidobacterium) may convert LA to CLA/HYA, enhancing anti-inflammatory and anti-obesity effects.

Conclusion

n-3 PUFAs and CLA in enriched meat and eggs offer substantial health benefits, especially for cardiovascular, inflammatory, and metabolic health. Species-specific enrichment strategies are essential due to differences in digestion (e.g., rumen barrier). Oxidative instability of PUFAs requires antioxidant co-supplementation for quality maintenance. CLA's inconsistent effects highlight the importance of isomer-specific studies. A balanced n-6: n-3 ratio and understanding of gut microbiota's role in CLA production provide promising future directions. Future research should prioritize multi-nutrient strategies, long-term clinical trials, and personalized nutrition approaches to maximize the health potential of functional animal products.

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CRISPR-CAS GENE EDITING IN AGRICULTURE: A TRANSFORMATIVE TOOL FOR SUSTAINABLE CROP IMPROVEMENT

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Abstract
CRISPR-Cas (Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated proteins) technology has emerged as a transformative tool in modern agricultural biotechnology. This article discusses the underlying mechanisms of CRISPR-Cas systems and their wide-ranging applications in crop improvement. With the ability to precisely and efficiently edit plant genomes, CRISPR-Cas is revolutionizing trait enhancement, from increased yield and nutritional value to improved resistance against biotic and abiotic stresses. Real-world examples, such as India's first genome-edited rice varieties—DRR Rice 100 (Kamla) and Pusa DST Rice 1—demonstrate its vast potential in promoting sustainable agriculture and climate-resilient food systems.

Introduction

CRISPR-Cas (Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated proteins) technology has revolutionized genetic engineering by enabling precise, efficient, and cost-effective genome editing. Since its inception, CRISPR-Cas has found extensive applications in agriculture, offering solutions to enhance crop yield, nutritional quality, and resistance to biotic and abiotic stresses. This article explores the mechanisms of CRISPR-Cas, its applications in agriculture, and real-world examples that demonstrate its potential to transform modern farming practices.

Applications in Agriculture

1. Enhancing Crop Yield and Quality

- Rice Varieties in India: The Indian Council of Agricultural Research (ICAR) has developed two genome-edited rice varieties, 'DRR Dhan 100 (Kamala)' and 'Pusa DST Rice 1', which require less water while maintaining or increasing yield. These varieties address the challenges of water scarcity and food demand in water-stressed regions.
- Tomato Sugar Content: Chinese scientists have utilized CRISPR to increase glucose and fructose levels in tomatoes by 30%, enhancing their sweetness without affecting size.

2. Developing Disease and Pest Resistance

- Citrus Canker Resistance: CRISPR-Cas9 has been employed to edit the CsLOB1 gene in citrus plants, conferring resistance to citrus canker, a devastating bacterial disease.
- Powdery Mildew in Grapes and Tomatoes: Editing MLO genes in grapes and tomatoes has resulted in increased resistance to powdery mildew, reducing the need for chemical fungicides.

3. Improving Abiotic Stress Tolerance

- Drought-Resistant Maize: CRISPR-Cas9 technology has been used to develop maize varieties with enhanced drought tolerance, ensuring stable yields under water-limited conditions.
- Salt-Tolerant Rice: By targeting specific genes, researchers have created rice varieties capable of thriving in high-salinity soils, expanding cultivable land areas.

4. Enhancing Nutritional Content

- GABA-Enriched Tomatoes: In Japan, CRISPR-edited tomatoes with increased γ-aminobutyric acid (GABA) levels have been commercialized, offering potential health benefits such as reduced blood pressure.
- Vitamin D-Fortified Tomatoes: Editing the 7-DR2 gene in tomatoes has led to increased provitamin D_3 content, addressing vitamin D deficiencies in human diets.

5. Extending Shelf Life and Reducing Waste

- Non-Browning Produce: CRISPR has been used to knock out polyphenol oxidase (PPO) genes in mushrooms, bananas, and lettuce, resulting in non-browning varieties that reduce food waste and enhance visual appeal.

Mechanism of CRISPR-Cas in Plants

The CRISPR-Cas system is a powerful genome-editing tool adapted from a natural defence mechanism found in bacteria. In plants, it enables precise modifications at specific genomic locations, allowing for targeted gene knockouts, insertions, or replacements.

Key Components

1) Cas Nuclease (e.g., Cas9 or Cas12a): An enzyme that cuts DNA at a specific location.
2) Guide RNA (gRNA or sgRNA): A synthetic RNA molecule that directs Cas9 to the target DNA sequence through base-pairing.
3) Target DNA: A specific gene sequence in the plant genome that is to be edited.
4) PAM (Protospacer Adjacent Motif): A short sequence (like NGG for Cas9) next to the target site, essential for Cas binding and activity.

Step-by-Step Mechanism

1. Designing gRNA
   - The gRNA is designed to be complementary to the target sequence in the plant genome.
   - It is fused with a scaffold that binds to Cas9.

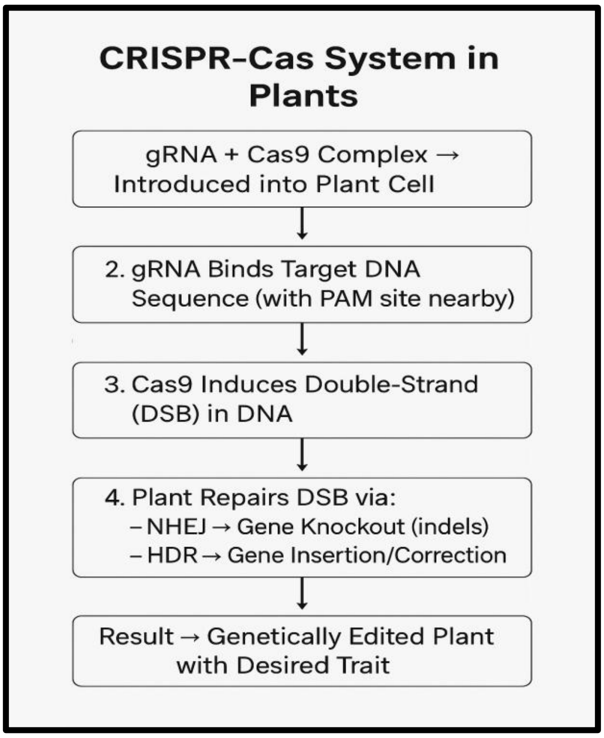
2. Delivery into Plant Cells
   - The CRISPR-Cas9 complex is delivered into plant cells via:
   - Agrobacterium-mediated transformation,
   - Gene gun (biolistics),
   - PEG-mediated transfection in protoplasts,
   - Viral vectors.

3. Target Recognition and Binding
   - The gRNA guides Cas9 to the target DNA sequence via complementary base pairing.
   - Cas9 scans for the PAM sequence (e.g., NGG) near the target.

4. DNA Cleavage
   - Cas9 makes a double-strand break (DSB) at the target site.

5. DNA Repair by the Plant Cell

- The cell repairs the DSB using one of the two pathways:
- Non-Homologous End Joining (NHEJ): Error-prone, leading to insertions/deletions (indels) → used for gene knockout.
- Homology-Directed Repair (HDR): Precise, requires a donor DNA template → used for gene insertion or correction.



India's First Genome-Edited Rice Varieties

The Indian Council of Agricultural Research (ICAR) has marked a significant milestone in agricultural innovation by developing the country's first genome-edited rice varieties – DRR Rice 100 (Kamla) and Pusa DST Rice 1. These varieties are expected to bring transformative benefits in crop productivity, climate resilience, and resource efficiency.

These new rice lines have been developed using CRISPR-Cas genome-editing technology, which enables targeted genetic modifications without the introduction of foreign DNA. The varieties fall under the SDN 1 and SDN 2 categories of genome editing, which are permitted under India's current biosafety framework for conventional crops.

The genome-editing project was launched in 2018 by ICAR under the National Agricultural Science Fund, with a focus on improving two prominent rice varieties — Samba Mahsuri and MTU 1010. After years of research, the effort has yielded two improved rice types with remarkable advantages:

- Up to 19% higher yield potential
- 20% reduction in greenhouse gas emissions
- Water savings of approximately 7,500 million cubic meters
- Enhanced tolerance to drought, salinity, and other climate-related stresses

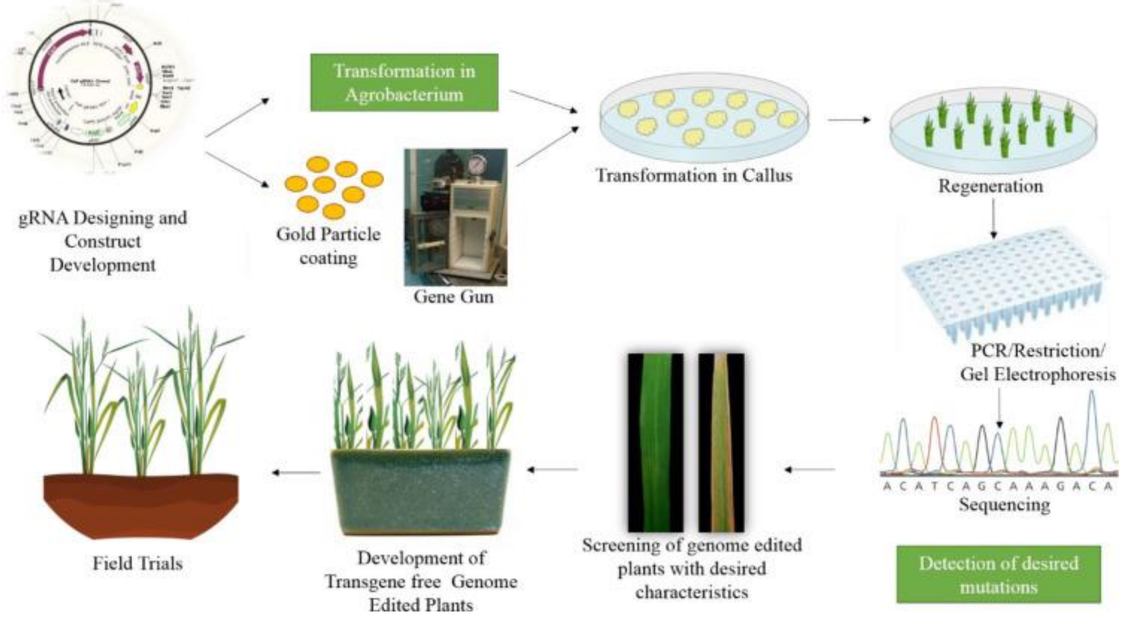


Figure: Genome editing in Rice (Source: https://pmc.ncbi.nlm.nih.gov/articles/PMC8525367/)

DRR Rice 100 (Kamla)

Developed by ICAR-IIRR, Hyderabad, this variety is derived from the popular Samba Mahsuri (BPT 5204). It has been designed to produce a greater number of grains per panicle and matures around 20 days earlier than the original, with a total crop duration of approximately 130 days. This shorter growing period contributes to lower water and fertilizer usage and helps curb methane emissions. The variety also features a strong, non-lodging stem and retains the grain quality of Samba Mahsuri.

Pusa DST Rice 1

This variant was developed by ICAR-IARI, New Delhi, using MTU 1010 as the genetic base. It demonstrates significant yield improvements — between 9.66% and 30.4% — particularly in saline and alkaline soils, offering the potential for an overall 20% increase in production in stress-prone areas.

Target Regions

These advanced rice varieties are recommended for diverse agro-climatic zones across India, including:

- Zone VII: Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, Puducherry, Kerala
- Zone V: Maharashtra, Chhattisgarh, Madhya Pradesh
- Zone III: Odisha, Jharkhand, Bihar, Uttar Pradesh, and West Bengal

Future Outlook

This achievement aligns with India's vision of achieving agricultural sustainability and self-reliance. Recognizing the importance of this technology, the Government of India allocated ₹500 crores in the 2023–24 Union Budget to promote genome editing in crop improvement. Building on the success of rice, ICAR is extending genome-editing research to other essential crops such as oilseeds and pulses.

The development of DRR Rice 100 and Pusa DST Rice 1 showcases India's progress in modern agricultural biotechnology and highlights the role of science and innovation in ensuring food security and climate-smart farming.

Conclusion

CRISPR-Cas genome-editing technology stands at the forefront of next-generation agricultural innovation. Its precision, efficiency, and affordability make it an ideal tool for addressing some of the most pressing challenges in global food security and environmental sustainability. The development of India's first genome-edited rice varieties, DRR Rice 100 and Pusa DST Rice 1, underscores the promise of this technology in enhancing crop productivity while conserving vital resources such as water and reducing greenhouse gas emissions. As India continues to invest in genome-editing research, particularly in pulses and oilseeds, CRISPR-Cas is poised to play a central role in achieving the nation's goals of sustainable farming and nutritional security. Widespread adoption and responsible regulation will be crucial in realizing the full potential of CRISPR-driven agriculture.

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UNDERSTANDING FARMERS FERTILIZER REDUCTION BEHAVIOUR IN INDIA: ECONOMIC, BEHAVIOURAL, AND POLICY DIMENSIONS

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Abstract

The overuse and imbalance of chemical fertilizers remain a pressing challenge in Indian agriculture, threatening soil fertility, water quality, and long-term sustainability. Despite numerous policy interventions and technological innovations, the persistence of excessive urea application highlights the need to better understand farmer decision-making processes. This paper systematically examines the determinants of farmers' fertilizer reduction behaviour in India, integrating economic, behavioural, institutional, technological, and environmental dimensions. A conceptual framework is developed to illustrate how these factors interact to shape farmer behaviour. The study also identifies key policy levers—including price alignment, soil health information, precision technologies, and behavioural nudges—while outlining research gaps related to subsidy delivery, nano-urea adoption, combined intervention trials, and nutrient balance accounts. The analysis demonstrates that fertilizer reduction is not merely an agronomic adjustment but a behavioural transition requiring coordinated policy, institutional, and technological support. Findings contribute to debates on sustainable nutrient management, offering pathways for transitioning Indian agriculture toward a more resource-efficient and climate-resilient future.

Keywords: Fertilizer reduction, Indian agriculture, Farmer behaviour, sustainability, Nutrient management, Policy interventions

Introduction

The use of chemical fertilizers has played a pivotal role in transforming Indian agriculture since the Green Revolution, ensuring food security for a rapidly growing population. Fertilizers, particularly nitrogenous inputs such as urea, have contributed significantly to increasing crop yields and stabilising grain supplies in the face of recurrent food shortages. India is now the world's second-largest consumer of fertilizers, with nitrogen alone accounting for over 60 percent of total nutrient application (Food and Agriculture Organization {FAO, 2021). However, the very success of fertilizers has created new challenges. Imbalanced and excessive use of chemical fertilizers—particularly nitrogen relative to phosphorous (P) and potassium (K)-has emerged as a major sustainability concern, leading to declining soil fertility, groundwater contamination, greenhouse gas emissions, and diminishing factor productivity (Lal, 2020; Singh and Singh, 2017).

Despite decades of policy reforms and awareness campaigns, the overuse of chemical fertilizers persists. Urea, kept artificially cheap through subsidies, is frequently over-applied, while the use of P&K fertilizers remains comparatively low due to higher relative costs. This imbalance has widened the nutrient ratio from the recommended 4:2:1 (N:P:K) to levels exceeding 8:3:1 in many states (Government of India, 2022). Such practices not only undermine soil health but also reduce long-term crop yields, threaten food system resilience, and impose environmental costs borne by society at large. Policymakers thus face a dual challenge: ensuring short-term food security while nudging farmers toward sustainable fertilizer practices that protect natural resources. At the same time, India faces the added complexity of managing fertilizer sustainability in the context of climate uncertainty. Increasing variability in rainfall, more frequent droughts and floods, and shifting agroecological zones exacerbate farmers' reliance on fertilizers as an "insurance" against yield loss (Mall *et al*., 2017). This makes the transition to more efficient and balanced fertilizer use not only an agronomic priority but also a climate adaptation imperative. This paper aims at systematically analysing the **determinants of farmers' chemical fertilizer reduction behaviour in India**, drawing from a wide spectrum of literature across agricultural economics, behavioural science, environmental studies, and policy analysis. By developing a comprehensive conceptual framework, the study integrates multiple explanatory dimensions—economic, behavioural, institutional, technological, and environmental-into a unified model. It further identifies key policy levers and research gaps that can guide the design of more effective interventions. In doing so, the study contributes to broader debates on sustainable agriculture, resource efficiency, and climate resilience in developing countries. Fertilizer reduction is not simply a question of lowering input use; it represents a **complex behavioural transition** that requires aligning farmer incentives, institutional capacities, technological innovations, and ecological realities. Understanding the determinants of this behaviour is therefore essential for ensuring both food security and environmental sustainability in the decades ahead.

Conceptual Framework

Farmer behaviour regarding fertilizer reduction in India cannot be explained by a single determinant; rather, it is shaped by the interplay of **economic rationality, behavioural psychology, institutional incentives, technological access, and environmental constraints**. For instance, a farmer may be economically motivated to overuse subsidised urea but behaviourally influenced by neighbours' practices, institutionally guided by a soil health card recommendation, technologically constrained by the absence of precision application tools, and environmentally driven by the agroecological conditions of soil type and rainfall patterns. An integrated conceptual framework is therefore necessary to understand these dynamics and inform policy design.

Existing literature has highlighted multiple determinants of farmers' fertilizer use behaviour. Economic incentives, such as subsidies and input-output price ratios, strongly influence application levels (World Bank, 2020). Behavioural factors, including risk aversion, peer influence, and reliance on traditional heuristics, also shape decision-making (Duflo et al., 2011). Institutional arrangements, such as the reach and quality of extension services, soil health card programmes, and the effectiveness of input dealer networks, further affect adoption of balanced nutrient practices (Gupta and Mishra, 2019). Additionally, technological innovations—such as neem-coated urea (NCU), nano-urea, precision farming tools, and biofertilizers—offer potential yield-safe alternatives that can enable fertilizer reduction without compromising productivity (Sahrawat, 2021). Yet, adoption remains uneven and often constrained by infrastructural, informational, and trust deficits.

Recent policy debates have increasingly emphasised the need for **fertilizer demand-side reforms**, complementing traditional supply-side approaches. Initiatives such as the Soil Health Card scheme, Direct Benefit Transfer (DBT) for subsidies, and the promotion of NCU and nano-urea represent attempts to align farmer incentives with sustainability objectives. However, the effectiveness of these interventions remains contested, as studies often evaluate isolated measures rather than the combined effect of price, technology, and behavioural nudges (Narayanamoorthy, 2018; Gulati & Banerjee, 2021). This creates a pressing need for holistic research that explores how multiple determinants interact to shape fertilizer reduction behaviour.

Understanding the determinants of farmers' chemical fertilizer reduction behaviour in India requires a multi-dimensional framework that integrates **economic, behavioural, institutional, and environmental perspectives**. Fertilizer use is rarely a purely technical decision; rather, it emerges from a complex set of interacting incentives, perceptions, and constraints. The conceptual framework developed here draws from **behavioural economics, innovation adoption theory, and sustainability transitions literature** to explain why farmers may or may not reduce fertilizer use, even in the presence of technologies or policies that encourage efficiency.

Economic Determinants: At the most immediate level, farmers' choices are influenced by the **relative costs and benefits of fertilizer use**. The heavy subsidy on urea compared to P&K fertilizers has created a distorted nitrogen-to-P&K ratio, incentivising overapplication of nitrogen. Additionally, fertilizer is often perceived as a low-risk, yield-assuring input, particularly in contexts of climate variability and uncertain rainfall. The opportunity cost of reducing fertilizer is therefore seen as potentially high, even when scientific evidence shows diminishing yield returns. Economic constraints such as credit availability, market access, and transaction costs further influence decision-making, especially among smallholders.

Behavioural Determinants: Fertilizer reduction behaviour is also shaped by **psychological and social factors**. Farmers tend to rely on heuristics and established practices, often using fertilizer as an "insurance mechanism" against unpredictable yields. Peer influence, social norms, and trust in input dealers strongly affect adoption choices. Behavioural inertia, loss aversion, and risk-averse tendencies mean that farmers may continue with high-input strategies even when presented with evidence of inefficiency. Information asymmetries and limited exposure to field demonstrations further constrain learning.

Institutional Determinants: Institutional frameworks play a decisive role in structuring fertilizer use. Government subsidy policies, extension systems, soil health card programmes, and market regulations all create enabling or constraining conditions for change. Weak integration of SHC recommendations into PoS systems, limited capacity of extension agents, and fragmented farmer-producer organizations reduce the effectiveness of institutional support. At the same time, emerging digital agriculture platforms, cooperative structures, and private-sector partnerships represent opportunities to realign institutional incentives towards sustainability.

Technological Determinants: Availability and accessibility of **yield-safe technologies**-such as neem-coated urea, nano-urea, bio-stimulants, and precision nitrogen management tools-are crucial in lowering the risks of fertilizer reduction. Farmers are more likely to adopt reduction practices when technologies demonstrate yield neutrality or yield gains. However, adoption is often hindered by inadequate supply chains, insufficient demonstrations, and lack of tailored recommendations for specific agroecological zones. The conceptual framework thus emphasizes that technology adoption must be embedded in broader systems of trust, incentives, and extension.

Environmental and Agroecological Determinants: Fertilizer reduction decisions are also conditioned by **biophysical realities**. Soils with declining organic matter, nutrient imbalances, and groundwater depletion create feedback loops that reinforce fertilizer dependence. Regional agroecological diversity means that a one-size-fits-all approach is ineffective. Farmers in high-rainfall zones, for instance, may apply more fertilizer as a hedge against leaching losses, while those in semi-arid zones may rely more on irrigation-linked nutrient application strategies. Recognising the heterogeneity of agroecological conditions is therefore essential to designing location-specific interventions.

Integrated Framework: Taken together, these determinants suggest that fertilizer reduction behaviour is not determined by any single factor but emerges from an **interaction of economic incentives, behavioural patterns, institutional structures, technological availability, and environmental conditions**.

Determinants of Fertilizer Reduction Behaviour

Farmers' decisions to reduce chemical fertilizer use are shaped by a complex interplay of socio-economic, institutional, technological, and ecological factors. These determinants are not uniform across India but vary significantly by region, crop system, and household characteristics.

Socio-Economic Determinants: Household characteristics, including landholding size, income diversification, education, and access to credit, strongly influence fertilizer decisions. Larger and resource-rich farmers often have more capacity to experiment with alternatives such as organic manures, biofertilizers, or precision tools, while smallholders may perceive high risks in reducing chemical inputs. Education level and agricultural training also shape awareness of nutrient management and willingness to adopt sustainable practices. Gender dimensions are equally important, as women farmers may prioritize soil health and cost savings but often face constraints in decision-making authority and access to extension.

Institutional and Policy Determinants: The structure of subsidies and market regulations plays a decisive role. Distorted price incentives—particularly the relatively low price of urea compared to P&K fertilizers—encourage over-application of nitrogen. Institutional mechanisms such as Soil Health Cards (SHC), fertilizer Point-of-Sale (PoS) tracking, and direct benefit transfer (DBT) systems influence behaviour by shaping both information and affordability. The quality of extension services, farmer-producer organisations (FPOs), and cooperatives further mediates adoption of reduction practices. Policies that integrate technology promotion with risk-mitigation instruments have shown greater potential to alter behaviour than isolated interventions.

Technological Determinants: The availability, accessibility, and perceived reliability of alternatives to conventional fertilizers significantly determine reduction behaviour. Adoption of neem-coated urea (NCU), nano-urea, slow-release formulations, and precision nitrogen management tools (such as leaf colour charts and chlorophyll meters) enables farmers to maintain yields while reducing input intensity. However, uptake depends on local supply chains, farmer trust in new technologies, and evidence from peer demonstration. Lack of timely availability or doubts about effectiveness can constrain adoption despite policy push.

Environmental and Agroecological Determinants: Soil fertility status, irrigation availability, and cropping intensity also influence fertilizer demand and the scope for reduction. Farmers in high-input, irrigated regions such as Punjab and Haryana are more locked into fertilizer-intensive practices compared to rainfed regions where resource constraints already limit fertilizer use. Climatic variability and risk of yield loss under uncertain rainfall often drive “insurance fertilization,” where farmers apply more nitrogen than agronomically required. In contrast, farmers experiencing soil degradation or water quality concerns may be more receptive to reduction measures.

Behavioural and Cognitive Determinants: Perceptions, risk attitudes, and trust in institutions mediate farmer responses to fertilizer reduction policies. Behavioural economics literature highlights that farmer often use heuristics, social norms, and dealer recommendations rather than soil-test-based advice in decision-making. Peer influence, demonstration effects, and aspirational learning shape adoption pathways. Moreover, cognitive biases such as loss aversion make farmers reluctant to experiment with reduced input levels unless supported by credible risk-mitigation mechanisms.

Market and Value Chain Determinants: Fertilizer use is also linked to broader value chain dynamics. Contract farming arrangements, crop procurement policies, and output price support influence nutrient application intensity. When markets reward high yields without accounting for quality or sustainability, farmers are incentivized to maximise fertilizer use. Conversely, premium markets for residue-free produce, organic certification, or sustainability-linked value chains create economic incentives for fertilizer reduction. Dealers and local retailers act as crucial intermediaries, often influencing farmer behaviour more than extension agents due to trust and accessibility

Policy Levers for Fertilizer Reduction in India:

Reducing the overuse of chemical fertilizers requires a multi-dimensional policy framework that simultaneously addresses price distortions, information asymmetries, technological adoption barriers, and behavioural inertia. Policy interventions need to move beyond input-centric subsidies towards integrated solutions that incentivize efficiency, resilience, and sustainability.

Rationalising Price Distortions and Aligning Nutrient Subsidies: The existing subsidy framework disproportionately favours urea, creating an artificially low nitrogen-to-P&K price ratio. This has been a principal driver of imbalanced nutrient use in India. Rationalisation through inclusion of urea under the Nutrient-Based Subsidy (NBS) scheme, or by restructuring direct benefit transfer (DBT) mechanisms to reflect actual nutrient content, could correct price signals. A phased alignment would avoid farmer backlash while encouraging balanced application. Complementary investments in awareness campaigns and localized demonstrations should accompany subsidy reform to build trust and reduce perceived risks.

Enhancing the Effectiveness of Soil Health Cards (SHC): While the Soil Health Card initiative has scaled nationwide, its potential remains underutilized due to generic recommendations and weak integration with farmer decision points. Policy should emphasize:

- Generating **plot-specific and dynamic nutrient prescriptions** using digital soil maps and real-time data.
- Embedding SHC-based recommendations directly into fertilizer point-of-sale (PoS) machines, ensuring that advice is linked with transactions.
- Integrating SHC advice with mobile-based advisory platforms and extension campaigns, making nutrient management guidance more actionable and continuous.

Promoting Scalable and Yield-Safe Technologies: Technological innovation is a cornerstone for reconciling yield objectives with sustainability. Neem-coated urea (NCU), nano-urea, and precision nitrogen management tools have demonstrated yield-neutral or yield-positive outcomes under field conditions. However, policy must address the following gaps:

- Ensuring **timely supply and distribution networks** for innovative products, particularly in remote districts.
- Supporting **public–private partnerships** for large-scale demonstrations that validate performance across diverse agroecological zones.
- Designing **credit-linked incentives** (through Kisan Credit Cards or FPOs) to lower upfront adoption costs.
- Encouraging **R&D and localised adaptation** of emerging technologies, including bio-stimulants and customized slow-release formulations.

Risk Mitigation and Insurance Mechanisms: Fertilizer overuse often functions as an informal insurance mechanism against climatic uncertainty. Expanding access to **weather-indexed insurance** and linking pay-outs with sustainable nutrient practices could directly reduce risk perceptions. Policymakers should also:

- Bundle crop insurance with **input advisory services** to encourage optimal input use.
- Encourage parametric insurance products tied to soil moisture or rainfall variability.
- Promote integration of insurance with **climate advisory platforms**, creating a comprehensive risk management ecosystem.

Behavioural Nudges and Dealer-Side Interventions: Behavioural factors are central to fertilizer decisions, with farmers often relying on heuristics, peers, and local dealers. Effective levers include:

- Establishing **peer-learning platforms and farmer champions** to showcase successful reduction practices.
- Training fertilizer dealers to act as **nutrient advisors**, supported by incentive schemes that reward sustainable sales.
- Deploying **social recognition campaigns** (e.g., awards for "soil health leaders" at village/block levels) to shift community norms.
- Testing behavioural nudges such as **default SHC-based recommendations** printed on receipts or displayed at PoS counters.

Hotspot Targeting and District-Level Customisation: India's fertilizer imbalance is spatially concentrated, with certain districts experiencing severe nitrogen overuse and nutrient runoff. A **"hotspot strategy"** would enable sharper policy targeting by:

- Mapping **districts and blocks with highest fertilizer imbalance** using remote sensing, PoS, and groundwater data.
- Designing **cluster-based interventions** where subsidy reforms, demonstrations, and regulatory oversight are piloted intensively.
- Enabling **state governments to tailor strategies** for their agroecological zones, supported by central guidelines and funding flexibility.

Integrating Value Chains and Market Incentives: Policies must also align with demand-side incentives in food markets. Sustainable fertilizer reduction will be accelerated if output markets reward farmers for balanced practices. Key options include:

- Expanding **certification schemes** (e.g., organic, residue-free) with premium price channels.
- Linking **sustainable nutrient management** to procurement policies, especially in MSP crops.

- Encouraging agri-businesses and food retailers to **adopt sustainability-linked sourcing standards**, transmitting incentives upstream to farmers

Research Gaps

Despite significant policy experimentation, several knowledge gaps remain that require systematic investigation:

Farmer-Level Direct Benefit Transfer (DBT) Pilots: While fertilizer subsidies are currently routed through manufacturers, direct transfers to farmers have been proposed as a mechanism to enhance efficiency and curb excessive fertilizer consumption. Research is needed to design and pilot farmer-level DBT schemes, examining their effects on purchasing behaviour, crop productivity, equity across farm sizes, and administrative feasibility. Key questions include whether DBT improves targeting, reduces leakages, and encourages balanced nutrient application. Rigorous impact evaluations using household panel surveys and randomised pilot programmes would provide critical insights.

Long-Term Impact of Nano-Urea Across Agroecological Zones: Nano-urea has emerged as a potential disruptive technology promising reduced nitrogen application without yield loss. However, most evidence is derived from short-term trials or demonstration plots. Longitudinal studies across diverse agroecological zones—such as rainfed, irrigated, coastal, and arid regions—are needed to assess its long-term effects on yield stability, soil microbiome health, nutrient dynamics, and farmer adoption behaviour. Comparative trials and multi-season experiments would strengthen the evidence base and guide scaling decisions.

Randomised Evaluations of Combined Interventions: Most studies to date evaluate single interventions—such as neem-coated urea or Soil Health Cards—in isolation. Yet, farmers respond to bundles of price signals, information, and technology options. Randomised controlled trials (RCTs) and quasi-experimental designs should test the combined impact of interventions (e.g., subsidy reforms + soil cards + advisory services). Such evaluations can reveal complementarities, threshold effects, and unintended consequences, offering more realistic insights into farmer decision-making under complex conditions.

Nutrient Balance Sheets and Trade-Adjusted Accounts: India's fertilizer policy debates often focus narrowly on consumption levels, without fully integrating nutrient flows within broader food systems. Research is required to develop comprehensive nutrient balance sheets that account for imports, exports, crop uptake, soil residuals, and environmental leakages. Integrating trade-adjusted nutrient accounts would help policymakers anticipate transboundary impacts of fertilizer policies and ensure sustainability. System dynamics modelling, life-cycle assessments, and data integration from farm to national scales could support this agenda.

Epilogue

The challenge of reducing chemical fertilizer use in India lies at the intersection of economic incentives, behavioural patterns, institutional frameworks, and technological readiness. Farmers' decisions on nutrient application are not merely technical but are shaped by a complex interplay of factors—ranging from distorted input subsidies and yield-risk perceptions to advisory gaps, peer influences, and dealer dynamics. While existing interventions such as Soil Health Cards, neem-coated urea, and digital PoS systems have laid an important foundation, their current design and implementation have only partially addressed the systemic drivers of imbalance.

A sustainable pathway forward requires reorienting policies from input-maximisation towards **efficiency, resilience, and long-term soil health.** Rationalising price distortions between nitrogen and P&K fertilizers is critical for restoring balance, but pricing reforms alone will not suffice. Complementary investments in **knowledge systems, behaviourally informed extension, and risk mitigation tools** are essential to lower farmers' perceived risks and adoption barriers. In this regard, embedding SHC recommendations into real-time PoS transactions, expanding access to weather-indexed insurance, and strengthening local dealer networks as trusted advisors could generate significant behavioural change at scale.

Equally important is the role of **technological innovation**, particularly yield-safe options such as nano-urea, neem-coated urea, and precision nitrogen tools. When combined with behavioural nudges and social learning platforms, these technologies offer farmers the dual benefits of input savings and productivity protection. Spatially targeted hotspot interventions-focusing resources in districts with the most severe nutrient imbalances-would further improve the cost-effectiveness and impact of interventions.

The research gaps identified in this study highlight the need for **rigorous, evidence-based evaluation** of ongoing reforms. Randomised trials of combined interventions (price reforms, advisory services, and technology diffusion), long-term monitoring of nano-urea performance across agroecological zones, and the development of nutrient balance sheets that integrate trade-adjusted accounts are all critical areas for future inquiry. Such evidence would not only guide adaptive policymaking but also provide a stronger scientific foundation for India's international commitments on sustainable agriculture, climate mitigation, and food security.

Ultimately, fertilizer reduction in India must be framed not as a constraint on productivity but as a pathway to **resilient farming systems, healthier soils, and more resource-efficient growth**. By leveraging integrated policy levers-subsidy rationalisation, innovation diffusion, behavioural nudges, and market alignment-India can transition towards a nutrient management regime that safeguards farmer livelihoods while delivering long-term ecological and economic benefits.

Conclusion

Fertilizer reduction in Indian agriculture represents both an agronomic challenge and a behavioural transition. Excessive and imbalanced use of chemical fertilizers has undermined soil fertility, environmental health, and long-term productivity. Determinants of fertilizer reduction behaviour are multifaceted, spanning economic incentives, behavioural biases, institutional capacities, technological availability, and environmental conditions. An integrated conceptual framework reveals the interdependence of these factors, highlighting the need for holistic policy design.

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ENHANCING FOOD SECURITY THROUGH AGRICULTURAL EXTENSION SERVICES

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Abstracts

Food security remains a pressing global challenge, especially in developing regions where agricultural productivity is low. Agricultural extension services comprising the dissemination of information, training, and technological innovations play a pivotal role in improving agricultural productivity, sustainability, and livelihoods. This article explores the theoretical foundations and practical impacts of agricultural extension services in enhancing food security. It delves into key models and frameworks of extension, evaluates successful case studies, and highlights policy implications for future interventions.

Keywords: Innovation, Productivity, Food, Agricultural, Extension, Security

Introduction

Food security is defined by the Food and Agriculture Organization (FAO) as a condition where all people, at all times, have physical and economic access to sufficient, safe, and nutritious food (FAO, 2006). Despite global efforts, over 735 million people remained chronically undernourished in 2023 (FAO, 2023). One of the fundamental strategies to tackle food insecurity is enhancing agricultural productivity, particularly among smallholder farmers who dominate the agricultural landscape in many developing countries.

Agricultural extension services are critical tools in achieving this. These services function as a bridge between research institutions and farmers, facilitating the flow of knowledge, technologies, and innovations. They not only contribute to improved yields and resource use but also address climate resilience, market access, and nutritional outcomes (Anderson & Feder, 2007).

Theoretical Foundations of Agricultural Extension

Diffusion of Innovations Theory

A foundational theory underpinning extension services is Everett Rogers' Diffusion of Innovations (1962). Rogers posits that innovations spread through specific channels over time among members of a social system. Extension agents act as change agents who influence adoption through knowledge sharing, persuasion, decision-making, implementation, and confirmation stages.

The model classifies farmers into five adopter categories: innovators, early adopters, early majority, late majority, and laggards. Understanding these categories allows extension services to tailor strategies that effectively promote new agricultural practices.

The Agricultural Knowledge and Information System (AKIS)

The AKIS framework (Rivera *et al.*, 2005) integrates research, education, and extension within an information system. It emphasizes the interactive nature of knowledge creation and dissemination among various actors, including researchers, farmers, NGOs, and the private sector. This systemic perspective is essential for addressing complex challenges like climate change and food insecurity.

Participatory Extension Approaches

Traditional top-down extension models have evolved into participatory approaches, where farmers are active stakeholders in knowledge generation and dissemination. Concepts such as Farmer Field Schools (FFS) promote experiential learning, peer exchange, and empowerment (Braun *et al*., 2000). These methods align with the principles of adult learning and are more sustainable in the long run.

Agricultural Extension and Food Security Linkages

Productivity Enhancement

Extension services directly affect food availability by promoting improved agronomic practices, high-yielding varieties, soil fertility management, and pest control. A meta-analysis by Davis *et al*. (2012) found that effective extension programs could increase crop yields by up to 30%.

Climate Resilience

Climate change poses a severe threat to food security. Extension services contribute to resilience through climate-smart agriculture (CSA), which includes practices like conservation agriculture, integrated pest management, and agroforestry (Lipper *et al*., 2014). Extension agents are instrumental in contextualizing these technologies for local ecosystems.

Nutrition and Food Utilization

Extension services also address food utilization by promoting the cultivation and consumption of diverse, nutrient-rich crops. For instance, biofortified crops (e.g., orange-fleshed sweet potatoes rich in vitamin A) have been disseminated through targeted extension campaigns (Low *et al*., 2007).

Market Access and Income

Food security is as much about economic access as it is about availability. Extension services facilitate market access by linking farmers to value chains, improving post-harvest handling, and providing market information systems. ICT-based services, such as mobile platforms, are increasingly being used to bridge information asymmetries (Aker, 2011).

Challenges in Extension Service Delivery

Human resource constraints: Many extension systems face a shortage of qualified personnel.

Gender disparities: Women, despite being key agricultural actors, often have limited access to extension services.

Institutional fragmentation: Coordination among stakeholders is often weak.

Funding and sustainability: Many public extension systems are underfunded and overly reliant on donor support.

Policy and Future Directions

To enhance the impact of extension services on food security, the following policy recommendations are suggested:

- Invest in ICT infrastructure to expand digital extension services.
- Promote gender-responsive programs to ensure inclusive access.
- Encourage public-private partnerships (PPPs) to leverage innovation and financing.

Conclusion

Agricultural extension services are a cornerstone of efforts to achieve food security, particularly in regions with smallholder-dominated farming systems. By enhancing productivity, promoting resilience, and supporting market engagement, these services offer a multifaceted solution to hunger and malnutrition. However, realizing their full potential requires systemic investment, inclusive approaches, and adaptive policies that reflect the complexities of modern agriculture.

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ECO-FRIENDLY SEED PRIMING IN HORTICULTURAL CROPS: EVALUATING NEEM LEAF POWDER AS A NATURAL ALTERNATIVE TO GA_3

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Abstract
Seed germination in certain horticultural crops such as marigold (*Tagetes* spp.) and cucumber (*Cucumis sativus* L.) often faces challenges for which gibberellic acid (GA_3) is commonly used as a seed priming agent to enhance germination. However, the use of synthetic plant growth regulators may not align with organic or sustainable practices. This study was aimed to explore an eco-friendly alternative to GA_3 by evaluating the potential of neem (*Azadirachta indica*) leaf powder as a seed priming agent. An experiment was conducted under laboratory conditions to assess and compare the germination performance of seeds primed with GA_3 and those treated with neem leaf powder. The results, in case of marigold, indicated that GA_3 @ 200 ppm for 24 hours resulted in the highest germination (86.62%) and the highest seedling dry weight (5.72 mg). Likewise, the marigold seeds primed with neem leaf powder @ 4% for 24 hours resulted in a germination of 82.63% and seedling dry weight of 5.10 mg. Similarly, GA_3 @ 200 ppm for 24 hours resulted in the highest germination (87.33%) in case of cucumber, whereas, germination per cent in case of cucumber seeds treated with neem leaf powder @ 4% for 24 hours gave germination of 85.58%. Therefore, the overall results highlight that GA_3 is an effective priming agent to improve the seed quality parameters, while also emphasizing that seed priming with neem leaf powder also serves as a potent and eco-friendly method to enhance the quality parameters of marigold and cucumber seeds. The results thus reveal that neem leaf powder exhibited comparable effectiveness to GA_3, with only minor variations in germination parameters, suggesting its potential as an eco-friendly priming alternative.

Keywords: GA_3, Neem leaf powder, Organic priming

Introduction

Marigold (*Tagetes* spp.) is a widely used ornamental and medicinal plant, renowned for its bright flowers, pest-repellent properties and ease of cultivation. This plant has a long standing reputation in traditional medicine, where it is utilized for various ailments including skin issues, wounds and burns, conjunctivitis, poor vision, menstrual irregularities, varicose veins, hemorrhoids and duodenal ulcers. Cucumber (*Cucumis sativus* L.) is an annual climbing herbaceous plant that belongs to Cucurbitaceae family. It is widely consumed as a nutritious vegetable, suitable for use in both fruit and vegetable dishes (Li et al. 2022). It is known for its high flavonoid content that scavenges free radicals and have an antioxidant property. However, germination and seedling vigour, in both these crops, are often hampered by unfavorable environmental conditions or seed dormancy. To address these challenges, seed priming has emerged as a promising method to enhance the physiological and biochemical processes of seeds prior to sowing. GA_3 is effective in overcoming both physiological and physical seed dormancy, enhancing germination even under challenging conditions. Moreover, GA_3 can improve seed vigour by increasing germination rate and promoting key growth metrics, particularly in seeds subjected to stress. Similarly, neem (*Azadirachta indica*) also has the potential to enhance seedling health and increase resistance to diseases (Galappaththi et al. 2021). Additionally, neem seed extract has demonstrated significant antioxidant activity (Revathi & Thambidurai 2019). The deterioration of seed quality during storage is primarily caused by free radical damage and pathogenic influences. This study aims to assess the effects of seed priming with GA_3 and neem powder, both individually, on the germination rate, seedling vigour and early growth parameters of marigold and cucumber. The main objective of this experiment is to identify effective, eco-friendly priming treatments that can be applied to enhance marigold and cucumber cultivation.

Methodology:

The experiment was conducted using a completely randomized design (CRD) with six treatments and three replications:

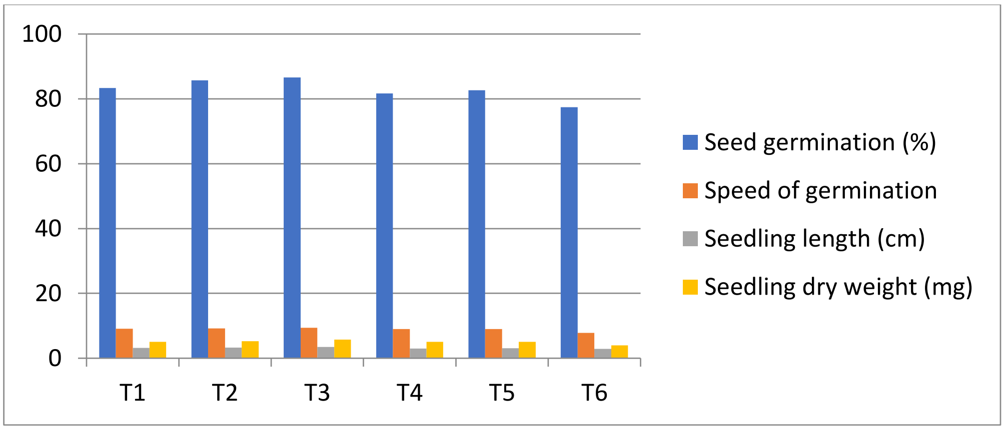
T_1: Seeds primed with GA_3 at 100 ppm for 24 hours
T_2: Seeds primed with GA_3 at 150 ppm for 24 hours
T_3: Seeds primed with GA_3 at 200 ppm for 24 hours
T_4: Seeds primed with Neem leaf powder solution @ 4 % for 18 hours
T_5: Seeds primed with Neem leaf powder solution @ 4 % for 24 hours
T_6: Control (Hydro-primed seeds)

Procedure:

Cucumber and marigold seeds were sterilized in sodium hypochlorite @ 1% for 10-15 seconds and then seeds are washed with distilled water. The prepared solutions are poured into the beakers and the seeds of both crops are immersed in them accordingly for specified time duration. After completion of specified time, seeds of both marigold and cucumber are taken out and put on blotter paper for air drying. Observations recorded are Germination percentage, Speed of Germination, Seedling length (cm) and Seedling dry weight (mg).

Observations recorded:

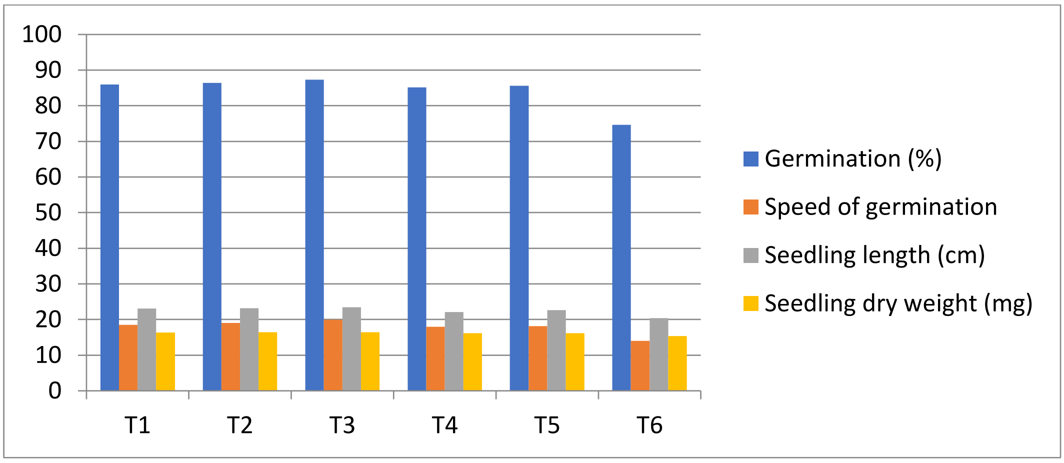
For marigold seeds, the data recorded is presented in the graph below:



The data recorded shows that the maximum value of seed germination (%), speed of germination, seedling length (cm) and seedling dry weight (mg) were reported in T_3, that is, GA_3 @ 200 ppm for

24 hours. However, these values are found comparable to the seeds treated with Neem leaf powder@ 4% for 24 hours i.e. T_5, thus indicating neem leaf powder to be a potent alternative to the seed priming with GA_3.

For cucumber seeds, the data recorded is presented in the graph below:



Among the cucumber seeds, the maximum germination percentage, speed of germination, seedling length (cm) and seedling dry weight (mg) were found in seeds primed with GA_3 @ 200 ppm for 24 hours i.e. T_3. This value was comparable to the results obtained after priming of seeds with neem leaf powder @ 4% for 24 hours, **thus indicating neem leaf powder to be a potent alternative to the seed priming with** GA_3.

Conclusion

These findings support the use of GA_3 and neem powder as effective seed priming agents. However, the eco-friendly nature of neem further contributes to sustainable agricultural practices, thus making it a suitable alternative to chemical seed treatment for enhancing seed germination, seedling vigour and overall growth. Organic treatments are cost-effective and align well with organic and sustainable farming systems, making them a preferred choice for enhancing seed quality and crop performance naturally.

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FUTURE FARMING SCOPE IN GUJARAT

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Abstract

Agriculture in Gujarat is undergoing a paradigm shift with the integration of natural farming, advanced technologies, and sustainable practices. This article highlights the scope of future farming in Gujarat, focusing on natural and organic farming, greenhouse and hydroponics, high-value horticulture, renewable energy integration, and food processing industries. The future of farming in Gujarat lies in diversification, value addition, and technological innovation, which can enhance farmers' income, ensure food security, and contribute to sustainable rural development.

Keywords : Future Farming, Gujarat, Sustainable Agriculture, Horticulture, Agri-Tech

Introduction

Gujarat has been at the forefront of agricultural development in India. With 60% of its population dependent on agriculture, the state has adopted various innovative farming methods to cope with challenges such as water scarcity, soil degradation, and climate change. The future of agriculture in Gujarat will be shaped by sustainability, diversification, and technology-driven practices.

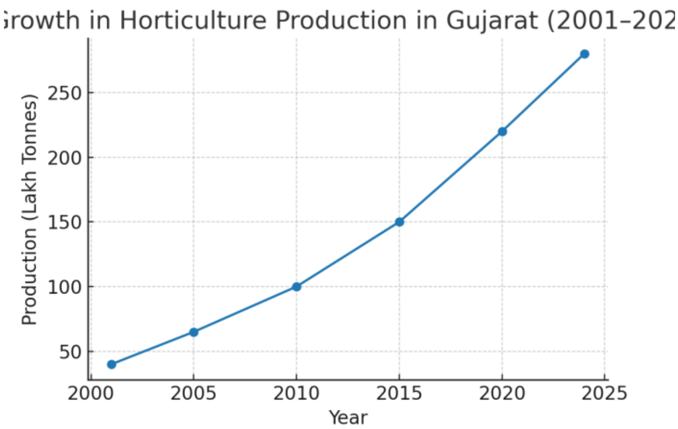

Figure: Horticulture Production Growth in Gujarat

Emerging Farming Opportunities in Gujarat

1) Natural & Organic Farming : Gujarat aims to expand natural farming from 3% to 25% by 2047, reducing dependency on chemicals and improving soil fertility. Districts like Dang are already fully chemical-free, setting examples for others.
2) High-Value Horticulture : Horticulture has shown significant growth in Gujarat. Crops such as mango, pomegranate, banana, and dragon fruit (Kamalam) are gaining global recognition. Expansion in protected cultivation can enhance productivity and export potential.

3) Greenhouse & Hydroponics Farming : Greenhouse and hydroponic systems provide year-round cultivation, higher yields, and efficient water usage. These methods are suitable for high-value crops like capsicum, tomato, and strawberries, and are supported by government subsidies.
4) Agritech, AI & IoT Integration : With the rise of agritech startups, digital solutions such as smart irrigation, blockchain traceability, and AI-driven crop advisory are becoming vital. These innovations improve efficiency and market connectivity.
5) Renewable Energy & Biofuels : Programs like PM-KUSUM support solar-powered irrigation, while biogas and ethanol projects from crop residues and dairy waste create additional income streams for farmers.
6) Food Processing & Value Addition : With GI-tagged crops such as Gir Kesar mango and Bhalia wheat, Gujarat has immense opportunities in food processing, including juices, chips, ready-to-eat snacks, and export-oriented products.

Table: Government Schemes Supporting Future Farming in Gujarat

Scheme	Objective	Benefit to Farmers
PM-KUSUM	Promote solar irrigation pumps	Reduce electricity cost, sell surplus power
Paramparagat Krishi Vikas Yojana (PKVY)	Encourage organic farming	Financial support, training
MIDH (Mission for Integrated Development of Horticulture)	Boost horticulture crops	Subsidy for infrastructure, better seeds
Agri Infrastructure Fund	Promote agri-logistics & storage	Low-interest loans for storage, cold chains

Conclusion

The future of farming in Gujarat is promising, driven by natural farming, advanced technologies, and strong government support. By embracing diversification, value addition, and renewable energy integration, Gujarat can become a model state for sustainable agriculture in India.

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INSECT-BASED PROTEINS: A SUSTAINABLE SOLUTION FOR GLOBAL FOOD SECURITY

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Abstract

Insect-based proteins are gaining attention as a sustainable alternative to conventional protein sources for both human consumption and animal feed. They offer high nutritional value, require minimal environmental resources and support circular economy models by converting organic waste into high-quality protein. While their benefits include efficient feed conversion, reduced greenhouse gas emissions and potential for enhancing food security. However key challenges remain, which include consumer acceptance, regulatory barriers and economic scalability. Advances in processing, strategic marketing and comprehensive regulations are essential for their mainstream adoption. Insect proteins hold potential in shaping future food systems by addressing global nutrition and sustainability demands.

Key words: Insect protein, sustainable nutrition, entomophagy, alternative proteins, circular economy.

Introduction

Insect-based proteins are increasingly recognized as a sustainable alternative to traditional protein sources for both human consumption and animal feed. This shift is driven by the need to address global food security challenges, environmental concerns and the growing demand for protein. Insects offer numerous advantages, including high nutritional value, efficient feed conversion and low environmental impact. However, there are also challenges related to consumer acceptance, regulatory frameworks, and safety concerns that need to be addressed to fully explore the potential of insect-based proteins.

Nutritional and Environmental Benefits

i. Insects are a rich source of high-quality protein, essential amino acids and beneficial fats, often surpassing traditional protein sources like beef and chicken in protein content, which can range from 30% to 85% on a dry matter basis (Shah et al., 2022) (Chukwudi et al., 2024). Moreover, insect farming requires significantly less land, water and feed compared to conventional livestock, making it a more environmentally friendly option for protein production (Oliveira et al., 2024). Addressing the regulatory and safety concerns associated with insect consumption will be crucial to enhancing consumer acceptance and promoting its widespread use (Perez-Fajardo et al., 2023). Additionally, innovative processing methods can improve the palatability and marketability of insect-based products, thereby increasing greater consumer interest and acceptance (Oliveira et al., 2024).

ii. They require significantly less land, water and feed compared to conventional livestock, and they emit lower levels of greenhouse gases, making them an environmentally friendly option (Dallao, 2024) (Oliveira et al., 2024). Overall, insect-based proteins present a promising solution to the growing demand for sustainable food sources, provided that regulatory frameworks and consumer perceptions are effectively addressed. To maximize the benefits of insect-based proteins, it is essential to implement comprehensive regulatory frameworks that ensure food safety and promote consumer trust in these alternative protein sources.

iii. Insects can convert low-value organic byproducts into high-value protein products, supporting circular economy models and reducing waste (Karmakar, 2024) (Oliveira et al., 2024). Incorporating insect-based proteins into diets could significantly enhance food security while also contributing to environmental sustainability, provided that consumer acceptance and regulatory challenges are adequately addressed (Oliveira et al., 2024) (Dong et al., 2024).

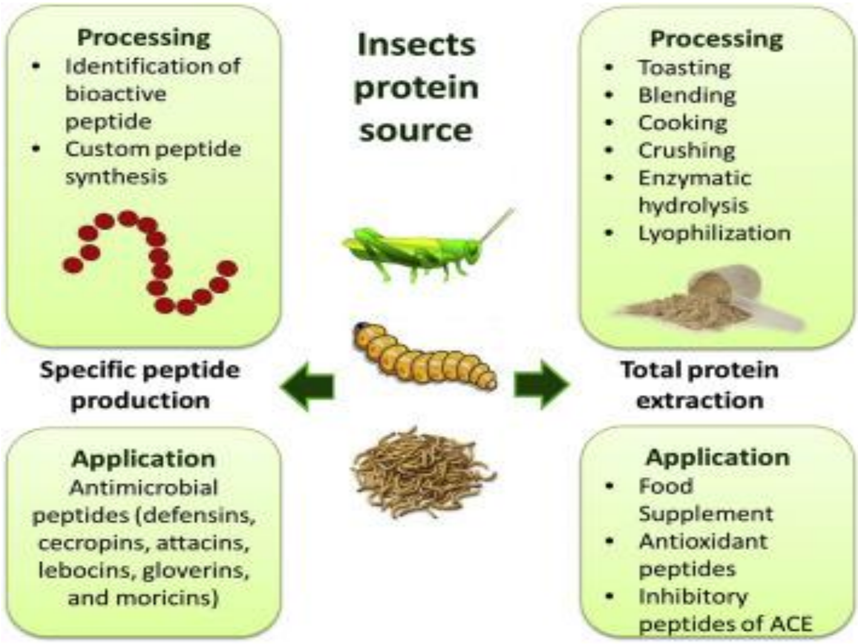

Fig. 1: Recent advances in insect protein processing and potential applications.

Source:(de Castro et al.)

Applications in Human and Animal Nutrition

i. Insect proteins can complement existing animal and plant-based protein sources, potentially becoming a staple in future food chains (Perez-Fajardo et al., 2023). As the demand for protein continues to rise globally, integrating insect proteins into both human diets and animal feed could play a crucial role in achieving sustainable food systems (Oliveira et al., 2024) (Dallao, 2024).

ii. In animal nutrition, insect protein is seen as a promising alternative to fishmeal, which is unsustainable and expensive. Insect meal has been approved for use in aquafeeds by the European Union, highlighting its potential in aquaculture (Toviho & Bársony, 2020) (Vale-

Hagan et al., 2023). This integration not only addresses nutritional gaps but also supports the transition towards more resilient and sustainable food systems globally.

iii. For human consumption, insects can be integrated into familiar food products to improve palatability and acceptance, addressing the "yuck" factor associated with entomophagy (Dallao, 2024) (Mancini, 2020). Strategies such as processing insects into familiar forms and conducting educational campaigns can help overcome cultural barriers and enhance consumer acceptance of insect-based foods (Dallao, 2024). By addressing these challenges, the integration of insects into diets can be accelerated, promoting both sustainability and nutrition.

Challenges and Barriers

i. Consumer acceptance remains a significant barrier, particularly in Western cultures where entomophagy is not traditionally practiced. Educational campaigns and processing insects into familiar products are strategies to overcome this challenge (Dallao, 2024) (Vale-Hagan et al., 2023). Efforts to enhance consumer acceptance must focus on addressing cultural perceptions and improving the sensory attributes of insect-based foods to facilitate broader integration into diets (Dallao, 2024).

ii. Regulatory frameworks are needed to ensure food safety, manage potential allergenicity and mitigate contamination risks from pathogens and environmental toxins (Oliveira et al., 2024). Efforts to promote the acceptance of insect-based foods should also consider the emotional reactions consumers have towards insects, such as disgust, which can significantly influence their willingness to try these alternative protein sources (Hartmann & Bearth, 2019).

iii. Economic viability and scalability of insect farming are also concerns, with high initial R&D costs and the need for new value chains and standardization (Vale-Hagan et al., 2023). Developing effective marketing strategies that highlight the environmental and nutritional benefits of insect-based proteins could help shift consumer perceptions and increase acceptance in Western markets.

Future Prospects and Research Needs

i. The market for insect protein is expected to grow significantly, driven by its sustainability and nutritional benefits. However, more research is needed to explore its effects on digestibility, product performance and health impacts (Shah et al., 2022). To address these gaps, future research should focus on consumer behaviors and preferences regarding insect consumption, as well as the development of innovative products that enhance acceptability and market appeal.

ii. Technological advancements in processing and breeding methods can enhance the quality and marketability of insect-based products, promoting wider acceptance (Oliveira et al., 2024). To achieve this, it is crucial to conduct further studies that investigate the sensory attributes and cultural perceptions surrounding insect consumption, ultimately leading to more effective marketing and educational strategies.

iii. Collaborative efforts between the public sector, scientific community and legislative bodies are crucial to increase awareness and support the development of the insect protein industry (Vale-Hagan et al., 2023). This collaboration should also focus on creating comprehensive educational initiatives to inform consumers about the benefits of insect-based proteins and to address the stigma associated with their consumption.

Conclusion:

Insect-based proteins offer a promising solution to global food security and sustainability challenges. While their widespread adoption depends on overcoming cultural, regulatory and economic barriers. Continued research and innovation, along with strategic efforts to improve consumer acceptance, will be key to unlocking the full potential of insects as a sustainable protein source.

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NANOMATERIALS USED IN POST-HARVEST TREATMENTS AND THEIR BENEFITS FOR FOOD SAFETY

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Abstracts
Food production through the cultivation of various crops and the rearing of livestock is the primary goal of agricultural practices. In developing nations, it is seen as the foundation of the economy and is crucial to food security. Scientists are increasingly experimenting with novel methods to boost food production because of the world's growing population and the resulting increased need for additional food supply. The use of nanotechnology in modern agriculture helps crops' biochemical pathways by altering the cautious approaches to assessing environmental concerns and applying it to increase productivity. They are also applied to increased productivity and crop development. The essence of this study is to discuss the various nanomaterials used, in post-harvest storage of crops, their benefits and their safety.

Introduction
Agriculture is practiced for food production via the cultivation of varied crops and raising of livestock. It is considered the backbone economy for most developing countries as a vital role in progress and development. The rising population in the world results in] high demand for more food supply, and scientists and engineers are now practicing new methods to increase agricultural production (Baruah and Dutta, 2009). For the last several years, agriculture nanotechnology has focused on research and application to resolve agriculture and environmental issues sustainability, crop improvement, and enhanced productivity. Agricultural nanotechnology seems to be highly interesting for developing countries, regarding the decrease in hunger, underfeeding, and mortality rate in children (Gogos et al., 2012). Agricultural practices in Nigeria and other parts of the world are faced with countless and unprecedented encounters ranging from, climate change, high post-harvest losses, and constraints, continuous growing population to industrialization. (Ndlovu *et al.*,2020; Gothandam *et al.*, 2018).

Scientific research has shown the potential of nanotechnology in improving the various sectors of the economy such as medicine, physics, pharmacology chemistry, computer science and engineering, industries as well as agriculture sector (Ashraf *et al.*, 2021). Its application in the agricultural sector enhances the efficiency of agricultural inputs and providing solutions to agricultural problems for improving food productivity and security (Singh et al., 2021).The role of nanotechnology in agriculture, postharvest loss reduction, and food processing towards achieving food security cannot be over-emphasized. The unique properties of nanoparticles (NPs) give them the capability to alter typical chemicals and devices (Iswanathan *et al.*, 2019). Nanoparticles can be defined as natural and artificial materials with at least one dimension ranging from 1 nm to 100 nm and these materials can be organic, inorganic or polymeric compounds (Shang *et al.*, 2019).

Nanomaterials
Natural or synthetic materials made of organic, inorganic, or polymeric molecules that have at least one dimension between 1 and 100 nm are known as nanomaterials (Raliya *et al.*, 2018). Since NPs

produced using chemicals as reducing agents are cytotoxic, they cannot be utilized in biomedical or other applications.

Plants and microorganisms (bacteria, algae, and fungi) are used in the synthesis of nanoparticles using green nanotechnology because they are easier to create and more environmentally benign (Panpatte *et al*., 2016). This procedure uses a variety of plant species to produce copper, zinc, nickel, cobalt, silver, and gold nanoparticles (Prasad *et al*.,2017).

Nanomaterials used in post-harvest treatments

Nanomaterials plays significant roles in reducing post-harvest losses of agricultural crops by enhancing their shelf life, prevent spoilage, and maintain food quality. Here are some types of nanomaterials commonly used for the preservation of stored food:

- **Silver Nanoparticles (AgNPs):** it possesses antimicrobial properties which enable them to inhibit the growth of bacteria, fungi, and viruses, thereby extending the shelf life of food and reducing microbial contamination.
- **Zinc Oxide Nanoparticles (ZnO):** they have antimicrobial and antioxidant properties, which aids in preventing foodborne pathogens and thereby extending the freshness of food.
- **Titanium Dioxide Nanoparticles (TiO2):** they are widely used for their antimicrobial and UV-blocking properties, preventing food from degradation caused by sunlight and oxidation.
- **Copper Nanoparticles (CuNPs):** they have natural antibacterial properties, which help mitigate the growth of bacteria and other pathogens in food products.
- **Chitosan Nanoparticles:** it can be described as a biopolymer material derived from chitin (found in crustacean shells) and they possess antimicrobial and antioxidant properties. Chitosan nanoparticles serve as a protective layer around food crops thereby, reducing moisture loss and spoilage.
- **Nanocellulose:** it is usually derived from plant fibers and is used as a supporting agent in food packaging. It has excellent barrier properties against oxygen, moisture, and other environmental factors.
- **Carbon Nanotubes (CNTs):** they have exceptional mechanical strength and are used to create food packaging that is strong yet lightweight. They also have antibacterial and antimicrobial properties.
- **Polymeric Nanoparticle:** it possesses antimicrobial properties and can also serve as controlled-release carriers for preservatives. Polymeric nanoparticles such as poly (lactic acid) (PLA), poly(ε-caprolactone) (PCL), and polyhydroxy-alkanoates (PHA) are used in food packaging and coatings.
- **Nanostructured Lipid Carriers (NLCs):** they are used to encapsulate active ingredients like essential oils, vitamins, or preservatives, which can be slowly released to preserve food quality and freshness.
- **Clay Nanoparticles:** One of the commonly used clay nanoparticles used is montmorillonite which possess antimicrobial properties and barrier properties to gases and moisture, which help in preserving food crops in agricultural storage.
- **Gold Nanoparticles (AuNPs):** Gold nanoparticles possess some antimicrobial activity and can be used to enhance the shelf life of food products. They are also used for their biocompatibility and low toxicity.

Potential benefits of nanomaterials in Post-Harvest Treatments

- **Crop Enhancement**: agrochemical agents derived from nanotechnology are used to improve crop productivity and to reduce application of pesticides.
- **Water management:** Nanomaterials can be used to improve water retention in soil, the release of water to the atmosphere and enhance irrigation efficiency.
- **Crop Protection:** it involves the application of nano-sensors in crop protection and for the identification of diseases as well as the residue of agrochemicals. They also possess antimicrobial and antifungal properties for the inhibition of microbial growth and prevent food borne diseases.
  The antioxidant properties of nanomaterials prevent food degradation while maintaining their nutritional value.
- **Genetic engineering:** it usually involves the use of nanodevices for the genetic engineering of plants.
- **Fertilizers and nutrient delivery:** it can enhance the efficiency of applied fertilizers to the soil thereby improving the soil nutrients**.**
- **Disease detection and management:** it is used for the early detection of diseases and its effective management.
- **Soil remediation:** nanomaterials can help improve soil nutrients by removing contaminants and cleaning polluted soils.
- **Livestock health:** it can be used to develop more effective animal feed, improve animal health and reduce the use of antibiotics
- **Shelf life:** Nano materials used in post-harvest treatment enhances shelf Life and Freshness of food crops
- **Reduction of pesticide residues:** it also plays an important role in reducing pesticide residue in stored food crops

Challenges and Limitations of nanomaterials in Post-Harvest Treatments

- **Persistence of Nanomaterial in the environment:** Some nanomaterials may persist in the environment for long periods, potentially causing harm to ecosystems.
- **Lack of Standardized Testing and Regulations**: There is no universally accepted standards for the use of nanomaterials in food production and packaging. Different countries have varying regulations, and in some regions, there is no regulatory framework at all.
- **Cost and Scalability:** The synthesis of certain nanoparticles is usually very expensive, such as silver or gold nanoparticles, can incur high costs due to the materials and equipment required. The technology is difficult for small-scale or developing-world farmers due to its unaffordability.
- **Complexity of Nanomaterial Behavior:** Nanomaterials may behave differently in food systems compared to their behavior in isolated or laboratory conditions. The interactions between nanomaterials and various food components (e.g., fats, proteins, and acids) are still not fully understood.
- **Instability in Food Products:** Certain environmental factors, such heat, humidity, or UV light, might cause some nanomaterials to deteriorate or lose their efficacy. It is essential to guarantee the durability and effectiveness of nanomaterials in post-harvest procedures.

Conclusion

The use of nanomaterials in post-harvest processes has several potential advantages that could greatly improve food sustainability, quality, and safety. These materials offer a practical answer to many of the problems associated with food storage and preservation by extending shelf life, decreasing microbiological contamination, maintaining nutritional value, and providing creative packaging options. They are also a viable and sustainable choice for the food industry because of their affordability and biodegradable nature. To guarantee the efficacy and safety of nanomaterials used in food applications, more investigation and regulatory evaluations are required.

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AGROFORESTRY AND ECOLOGICAL SIGNIFICANCE OF *Kigelia pinnata*: A CLIMATE-RESILIENT MULTIPURPOSE TREE

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Abstract

Kigelia pinnata, is a versatile, climate-resilient species integral to agroforestry and ecological sustainability in tropical and subtropical Africa. This multipurpose tree thrives in diverse ecosystems, from savannas to rainforests, offering shade, improving soil fertility, and acting as a windbreak. Its deep roots prevent erosion, while nutrient-rich leaf litter enhances soil health, boosting crop yields in systems like alley cropping. Ecologically, it supports biodiversity by attracting pollinators like fruit bats and providing food for wildlife, contributing to natural pest control and forest regeneration. The tree sequesters significant carbon, aiding climate change mitigation, and conserves water by improving soil retention. Its bark, leaves, and fruits are valued in traditional medicine, crafting, and cosmetics, creating economic opportunities. Despite challenges like slow growth and overharvesting, *Kigelia pinnata* holds immense potential for sustainable agriculture and resilient landscapes.

Keywords: Agroforestry, Balam Kheera, Climate Resilience, Multipurpose Tree, Sausage tree

Introduction

Kingdom: Plantae	**Scientific Name:** *Kigelia pinnata*
Order: Lamiales	**Hindi Name:** Balam Kheera, Jhar fanoos (folk),
Family: Bignoniaceae	**English:** Sausage tree, Cucumber tree,
Genus: Kigelia	**Kannad:** Aanethoradu Kaayi, Mara Sowthae

Kigelia pinnata is native to a wide range of African ecosystems, from the dry savannas of Kenya to the wetlands of Uganda and the woodlands of South Africa (Orwa *et al.,* 2009). This is a medium-to-large tree, often reaching heights of 10–20 meters, is easily recognized by its broad canopy and distinctive fruits long, sausage-like pods that can grow up to a meter in length and weigh up to 7 kilograms (Neuwinger, 1996). These fruits, along with the tree's leaves, bark, and roots, have been used for centuries in traditional medicine, crafting, and cultural practices. Many modern medicines come from natural sources, like plants. Research shows that compounds in these natural products have a wide range of health benefits and medicinal properties. Traditional knowledge about how people use plants for healing has been key in creating medical guides and drug development. Out of about 400,000 plant species, only 6% have been tested for their biological effects, and just 15% have been studied for their chemical makeup (Cragg GM *et al.,* 1997). Kigelia pinnata grows well in various soils, including loamy red clay, rocky, or moist peaty soils, from sea level up to higher altitudes (Grace OM *et al.,* 2002). It thrives in deep, open soils along rivers, in open woodlands, high-rainfall savannas, shrublands, and rainforests. The tree is easily grown from seeds during the rainy season, and some have tried propagating it using cuttings (WOI 2007). It flowers between August and October and produces fruit from December to June. The tree sheds its leaves twice a year but never becomes completely bare. (Joffe P 2003). It is a cornerstone of agroforestry systems and a vital contributor to ecological resilience, offering a suite of benefits that address the pressing challenges of climate change, food security, and sustainable land management. As global temperatures rise, rainfall patterns shift, and soils degrade, *Kigelia pinnata* emerges as a climate-resilient, multipurpose tree that supports farmers, ecosystems, and communities across tropical and subtropical Africa. In agroforestry the practice of integrating trees into agricultural systems to enhance productivity, sustainability, and resilience *Kigelia pinnata* is a standout species. Its multipurpose nature means it serves multiple functions: providing shade, improving soil health, supporting biodiversity, and offering resources like medicine and timber (Akinnifesi *et al*., 2010).

Fig.1

Agroforestry Benefits of *Kigelia pinnata*

Shade and Microclimate Regulation

In the blistering heat of African farmlands, where temperatures can soar above 35°C, crops and livestock often suffer from heat stress. *Kigelia pinnata* acts as a natural canopy, its wide, dense foliage creating shade that lowers soil and air temperatures. This creates a microclimate a localized environment where conditions are cooler and more humid allowing crops like maize, millet, or vegetables to thrive in otherwise challenging conditions (Sileshi *et al.,* 2007). The shade also reduces evaporation, helping soils retain moisture longer, which is critical in regions with erratic rainfall (Mbow *et al*., 2014). In pastoral systems, *Kigelia pinnata* is a boon for livestock. In Tanzania and Kenya, farmers plant it in grazing fields to provide cattle with cool resting areas, which improves animal health and milk production (Grace *et al.,* 2016). For example, a study in Kenya found that shaded pastures increased milk yields by 10–15% compared to open fields, highlighting the tree's role in enhancing livestock productivity (Sileshi *et al.,* 2007).

Soil Fertility and Erosion Control

Soil degradation is a major challenge in tropical agriculture, where heavy rains and intensive farming strip away nutrients and erode topsoil. *Kigelia pinnata* addresses these issues through its deep root system and nutrient-rich leaf litter. The roots anchor soil, preventing erosion on slopes or riverbanks, while fallen leaves decompose into organic matter that enriches the soil with nitrogen, phosphorus, and other nutrients (Neuwinger, 1996). This natural fertilization improves soil structure, making it more porous and better able to retain water, which is vital in dryland farming systems (Akinnifesi *et al.*, 2010). In Malawi, farmers have reported higher crop yields when growing maize or beans near *Kigelia pinnata*, attributing this to the tree's soil-enriching properties (Orwa *et al.,* 2009). In alley cropping systems, where trees are planted in rows with crops grown in between, *Kigelia pinnata* reduces the need for synthetic fertilizers, cutting costs and environmental impact. A study in Zambia showed that agroforestry systems with multipurpose trees like *Kigelia pinnata* increased soil organic carbon by 20–30% over five years, demonstrating its long-term benefits for soil health (Mbow *et al.,* 2014).

Windbreaks and Boundary Planting

Strong winds can devastate crops, blow away topsoil, and make farming a constant battle. *Kigelia pinnata* serves as a natural windbreak, its robust trunk and thick foliage slowing down gusts and protecting fields. In agroforestry, it is often planted along farm boundaries or in hedgerows to shield crops like sorghum, millet, or groundnuts from wind damage (Sileshi *et al.,* 2007). In Zimbabwe, communities use *Kigelia pinnata* to mark property lines while benefiting from its protective qualities, especially in windy, semi-arid regions (Orwa *et al*., 2009). The tree's ability to grow in poor soils, such as sandy or rocky ones, makes it ideal for these roles. Its resilience ensures that it remains effective even in challenging environments, providing long-term protection for crops and reducing the need for replanting (Akinnifesi *et al*., 2010).

Ecological Significance of *Kigelia pinnata*

Biodiversity Support

Kigelia pinnata is a biodiversity hotspot in African ecosystems. Its large, bell-shaped flowers, which bloom at night and range from red to purplish-green, are a magnet for pollinators like fruit bats, bees, and birds. Fruit bats, in particular, are key pollinators, feeding on the nectar and spreading pollen across vast distances, which supports the tree's reproduction and genetic diversity (Harris & Baker, 2007). The bats also disperse seeds by eating the fruits and excreting seeds elsewhere, aiding forest regeneration in degraded landscapes (Grace et al., 2016). The tree's fruits, though inedible to humans, are a vital food source for wildlife, including baboons, monkeys, elephants, and porcupines. This supports a complex food web, as these animals attract predators and scavengers, creating a ripple effect of biodiversity (Neuwinger, 1996). In agroforestry systems, the presence of *Kigelia pinnata* encourages natural pest control, as birds and bats feed on crop-damaging insects, reducing the need for chemical pesticides. A study in South Africa found that farms with multipurpose trees like *Kigelia pinnata* had 25% fewer pest-related crop losses compared to monoculture fields (Sileshi *et al*., 2007).

Carbon Sequestration and Climate Resilience

As the world grapples with climate change, trees that store carbon are critical for mitigating global warming. *Kigelia pinnata* is a champion carbon sink, its large size and long lifespan allowing it to sequester significant amounts of carbon dioxide. In agroforestry systems, planting *Kigelia pinnata* alongside crops or in reforestation projects can turn agricultural landscapes into carbon storage hubs (Mbow *et al*., 2014). A study in Uganda estimated that mature *Kigelia pinnata* trees can sequester up to 500 kg of carbon per tree over their lifetime, making them a valuable tool for climate mitigation (Grace et al., 2016). The tree's resilience to drought, high temperatures, and poor soils makes it particularly suited to climate-challenged regions. In areas like northern Kenya, where rainfall is increasingly unpredictable, *Kigelia pinnata* is being integrated into reforestation efforts to restore degraded lands while providing shade and resources for communities (Orwa *et al*., 2009).

Water Conservation and Watershed Protection: Water scarcity is a growing concern in Africa, and *Kigelia pinnata* plays a crucial role in conserving this precious resource. Its deep roots reduce surface runoff, allowing rainwater to infiltrate the soil and recharge groundwater supplies. Along riverbanks, the tree's roots stabilize soil, preventing erosion that can clog waterways with sediment and harm aquatic ecosystems (Neuwinger, 1996). In Zambia, farmers have planted *Kigelia pinnata* near water sources to protect watersheds while benefiting from its shade and medicinal fruits (Orwa *et al*., 2009). In agroforestry systems, the tree's ability to improve soil water retention is a game-changer. By creating a more porous soil structure, *Kigelia pinnata* helps farms retain moisture during dry spells, reducing irrigation needs and supporting crop growth in water-scarce regions (Akinnifesi *et al*., 2010).

Multipurpose Uses for Communities

Traditional Medicine: Across Africa, the tree's bark, leaves, and fruits are used to treat a wide range of ailments, including skin infections, stomach disorders, and snakebites. Recent studies have validated these uses, showing that extracts contain antimicrobial, anti-inflammatory, and antioxidant compounds like verbascoside and kigelin (Grace *et al.,* 2016). For rural communities with limited access to modern healthcare, *Kigelia pinnata* is a vital resource (Jaca & Moteetee, 2018).

Crafting and Construction

The tree's durable wood is used for furniture, tools, and canoes, while dried fruits are crafted into containers or decorative items. In some cultures, the tree holds spiritual significance, used in rituals or as a talisman for protection (Neuwinger, 1996).

Livestocks and Agriculture

The leaves serve as fodder for livestock during dry seasons, when other forage is scarce. Fruits can be processed into animal feed or fermented for traditional brews in some regions (Orwa *et al*., 2009).

Cosmetics and Commercial Potential

Fruit extracts, rich in antioxidants and skin-tightening compounds, are increasingly used in cosmetics for anti-aging and skin care products. This creates economic opportunities for farmers, who can grow *Kigelia pinnata* for commercial markets, boosting local economies (Jaca & Moteetee, 2018).

Challenges and Considerations

Despite its many benefits, *Kigelia pinnata* presents some challenges. Its heavy fruits can pose a safety hazard if they fall, so it's best planted away from homes, paths, or livestock pens (Neuwinger, 1996). Overharvesting for medicinal or commercial purposes can threaten wild populations, underscoring the need for sustainable cultivation in agroforestry systems (Akinnifesi *et al.,* 2010). The tree's slow growth rate often taking 5–10 years to reach maturity requires patience, which can be a barrier for farmers seeking quick returns (Orwa *et al*., 2009). To overcome these challenges, farmers need support, such as access to seedlings, training on propagation techniques, and incentives for integrating *Kigelia pinnata* into their systems. Governments and NGOs can play a key role by promoting the tree in reforestation and sustainable agriculture programs, ensuring its benefits reach more communities (Mbow *et al*., 2014).

Conclusion

Kigelia pinnata, the sausage tree, is a climate-resilient, multipurpose marvel that transforms farms and ecosystems. From providing shade and enriching soils to supporting biodiversity and empowering communities, it is a vital tool for sustainable agroforestry in a changing world. Its ability to thrive in tough conditions and offer diverse resources makes it a beacon of hope for farmers and conservationists facing climate challenges. By planting and nurturing *Kigelia pinnata*, we can create greener, more resilient landscapes that sustain life for generations to come.

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FEEDS AND FEEDING MANAGEMENT IN BRACKISH WATER ORNAMENTAL FISH FARMING: AN OVERVIEW

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Introduction

Feed represents a significant component in the cost structure of brackish water aquaculture, accounting for approximately 60–70% of the total operational expenses. Developing nutritionally balanced aqua feed requires a thorough understanding of the specific dietary needs of the cultured species, careful selection of feed ingredients, precise feed formulation, and the use of suitable processing technologies to produce water-stable pellet feeds. The selection of feed materials varies widely based on the farming system being practiced.

The efficiency and effectiveness of a formulated feed are influenced by several critical factors, including:

- The formulation of the feed and the nutritional quality of the ingredients used
- The manufacturing techniques and the physical characteristics of the feed product
- Proper handling and storage practices to maintain feed quality
- Feeding strategies such as the type of feed used, methods of feed application, and feeding schedules
- The surrounding aquatic environment and the availability of natural food sources

Feed management refers to the strategic use of feed to ensure its optimal utilization, minimize wastage, reduce environmental impact, and achieve efficient feed conversion ratios along with maximum growth and productivity of fish and shrimp. Even a high-quality feed may yield poor results if feed management practices are inadequate, whereas a moderately formulated feed can deliver excellent outcomes when supported by effective feed management (ICAR – CIBA Training Manual 2021, 2022).

Nutrient classes of aquafeed

- ✓ Proteins and amino acids
- ✓ Carbohydrates
- ✓ Lipids and fatty acids
- ✓ Vitamins
- ✓ Mineral

Nutritional requirements

A fundamental understanding of the nutritional requirements of the target species is essential for effective feed formulation and preparation. The chosen feed must meet the nutritional needs of the cultured species. There are six essential nutrient groups viz proteins, lipids, carbohydrates, vitamins, minerals, and water—that play vital roles in growth, reproduction and maintaining health. The specific nutrient requirements vary among species based on their feeding behaviour, habitat conditions, and life stage. Therefore, it is crucial to formulate feeds that are nutritionally balanced with an ideal protein-to-energy ratio. Additionally, the feed must retain its nutrient content during feeding and avoid nutrient loss into the water. To achieve this, aquaculture feeds are developed using specialized processing techniques that help the diet remain stable in water until consumed, thus minimizing nutrient leaching (ICAR – CIBA Training Manual 2021,2022). The use of non-nutritive additives such as binders and preservatives is essential to enhance the stability and extend the shelf life of formulated feeds. Incorporating natural bio pigments into ornamental fish diets is crucial to sustain their vibrant body coloration in aquarium conditions. Careful selection of feed ingredients is necessary, taking into account their cost, availability, digestibility, and nutritional value. These aspects play a significant role in determining the overall cost, effectiveness, and performance of the formulated feed (Archana Sinha *et al*., 2019).

Types of feeds

Ornamental fishes can be provided with different types and forms of feed. Based on physical characteristics, feeds are classified into dry mash, flakes, sinking pellets, floating pellets (produced through extrusion), moist cake, and wet or paste feeds. Surface-feeding species can be offered mash feed, though it may pollute aquarium water if not properly managed. Slow-sinking feed is appropriate for mid-water or column feeders, while bottom feeders prefer moist cake or paste feeds.

Dry Feeds

These feeds are low in moisture, typically ranging from 6% to10%.

Types of dry feed include:

Mash Meal: This consists of finely powdered ingredients, either mixed according to a formula or combined without one, and is generally fed to early life stages such as fry.

Pellets: A blend of ingredients compressed into uniform shapes and sizes using mechanical or manual pellet-making tools.

Non-dry Feeds : These feeds contain significantly more moisture, usually between 18% and 70%.

Moist Feeds: These are formulated by mixing either wet and dry ingredients or by simply adding water to dry feed components. Moisture levels generally range between 18% and 40%.

Wet or Paste Feeds: Composed mostly of moist raw materials like trash fish, shrimp, beef heart, or live feeds, these have a moisture content of around 45% to 70% (Archana Sinha *et al*., 2019).

Due to difficulties in handling, storing, distributing, and maintaining the quality of wet and semi-moist feeds, the industry is gradually shifting toward dry feeds, which are produced using steam pelleting or extrusion technologies (ICAR – CIBA Training Manual 2021,2022).

Feed formulation

Feed formulation involves combining various raw materials to meet the specific nutritional needs of fish, depending on their species and stage of growth. The selection of ingredients should be based on their efficiency in supplying key nutrients such as protein, energy, essential amino acids, and essential fatty acids at the most economical cost. This approach is based on the assumption that the nutritional value of a particular nutrient remains consistent across different feed ingredients, allowing multiple sources to be blended in varying proportions to fulfill the dietary requirements of the fish. Achieving an optimal nutrient balance is more effective when multiple feed ingredients are used in combination.

- Ensure the crude protein content is properly balanced.
- Assess and adjust the digestible energy levels accordingly.
- Evaluate the content of essential amino acids and essential fatty acids. If they are insufficient, revisit the earlier steps—adjust the protein sources to meet amino acid requirements and modify lipid sources to fulfill essential fatty acid needs.

Feed formulation can begin once the proximate composition of the ingredients is known. The mathematical methods used in feed formulation are generally straight forward and have become increasingly accessible with the help of various software tools. When diets involve only a few ingredients and the levels of protein, energy, and minerals are predetermined, they can be developed using basic equations. In such cases, where amino acid and fatty acid balances are not critical, the ―Pearson square‖ method is a simple and effective tool. More complex formulations aimed at minimizing cost are developed using sets of simultaneous equations, forming the basis of the ―least-cost‖ formulation technique (Archana Sinha *et al*., 2019).

Steps of fish feed preparation

- Feed ingredients are finely ground and passed through a mesh sieve to achieve uniform particle size (Archana Sinha *et al*., 2019)
- The sieved feed materials and vitamin-mineral premix are then accurately weighed.
- All the weighed ingredients, excluding the vitamin-mineral mix, are thoroughly blended to form a consistent mixture (Archana Sinha *et al*., 2019)
- The combined ingredients are cooked in a large vessel, steam cooker, or mixer for about 15 minutes (Archana Sinha *et al*., 2019)
- The vitamin-mineral mixture is dissolved in water and then added to the hot, cooked feed dough to retain its nutritional value (Archana Sinha *et al*., 2019)
- The prepared dough is fed into a pelletizer to form noodle-like pellets.
- The pelleted feed is dried in a dryer at 50°C to minimize vitamin loss due to heat (Archana Sinha *et al*., 2019).
- Once dried, the noodle-shaped pellets are crushed using a hand grinder to obtain smaller pellets for feeding different sizes of fish (Archana Sinha *et al*., 2019)
- Dried pellet feed must be properly packed in polythene bags and stored on a raised wooden platform to prevent moisture absorption, and it should be used within a period of 3 to 4 months (ICAR – CIBA Training Manual 2021,2022)

Feeding

Fish should be fed every day at a fixed time, preferably by the same person. The quantity of feed provided should be just enough to be consumed quickly. Avoid overfeeding. To prevent both underfeeding and overfeeding, it is essential to determine the correct feeding rate and schedule. Feeding rate, frequency, and timing should be based on the growth stage and bodyweight of the fish. Feed acceptance and utilization also rely on favourable environmental conditions such as temperature and dissolved oxygen levels. Proper estimation of fish biomass is crucial to determine the accurate amount of feed needed. It is important to monitor the total number of fish, their average size, and weight in the culture unit. The feed requirement per feeding session can be calculated using the following formula:

Total Feed Amount = Average Fish Weight × Feed Rate (%) × Total Number of Fish / 100 (Archana Sinha *et al.*, 2019).

Frequency of feeding

The total daily feed requirement should not be given all at once. Proper scheduling and feeding frequency play a key role in effective feed management. Feeding times should be planned so that a larger portion of the feed is provided when the fish are likely to be most hungry. Brackish water fish species are typically fed 3 to 4 times per day. Increasing feeding frequency helps minimize periods of starvation and reduces the risk of stunted growth, leading to a more uniform size among fish. Ideally, feeding should be scheduled at least three times a day—morning, noon, and evening. Providing smaller portions of feed more frequently improves feed utilization and enhances feed conversion ratio (FCR). It is essential to have a system in place to monitor feed consumption. The next feeding should be adjusted based on how much of the previous feed was consumed. (ICAR – CIBA Training Manual 2015).

Water quality

The relationship between feeding and water quality in aquaculture is interrelated. Ensuring optimal, species –specific environmental parameters such as temperature, dissolved oxygen, pH, and salinity—supports proper feeding, promotes better growth, and enhances survival rates. However, when these parameters drop below ideal levels, cultured species become stressed, leading to reduced feed intake and poor growth performance. The accumulation of uneaten feed along with metabolic wastes results in elevated levels of BOD, ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4), contributing to eutrophication and deteriorating water quality. This poses a major management challenge, as feed and feeding practices are closely tied to effluent quality, which is often subject to regulation under water pollution control laws in many countries. Therefore, feeding strategies should aim to reduce nutrient wastage and faecal output while enhancing nutrient utilization and maintaining fish health (ICAR- CIBA Training Manual 2015,2021,2022).

Handling and storage of feeds

Efficient handling and storage practices on farms are vital aspects of good management. Since feed is made from perishable biological ingredients, it is susceptible to spoilage during storage. To avoid this, it is best to keep storage durations as short as possible. Even high-quality feed can degrade or lose nutritional value if stored improperly or for extended periods. Spoilage may result from oxidative reactions, microbial contamination, insect or rodent damage, and other chemical alterations. Feeds should be stored in a way that prevents contact between the bags and the floor or walls. Storage rooms must be completely waterproof, and ideally, designed to resist dampness. Therefore, various feed types such as wet, moist, and dry feeds require specific storage conditions. Wet feeds, with moisture content above 70%, should be kept at −30°C or lower for preservation. Standard freezer temperatures of −20°C are not suitable for long-term storage. Dry feeds should be maintained in cool, dry environments—ideally below 20°C with relative humidity under 75%.(ICAR – CIBA Training Manual 2021,2022).

Guidelines to be followed

1. Observation of fishes during feeding. It indicates the overall healthiness of fishes. Active feeding behaviour indicates everything is all right. However, poor feeding response should always be viewed seriously.

2. When temperature reduces suddenly, the feeding level should be reduced.
3. Stop feeding during stormy or extremely calm weather conditions. These conditions can lead to low dissolved oxygen.
4. Quality of feed must been sured before procurement.
5. Feed must be kept in cool, dry place, and utilized within three months of manufacture. For moist feeds and trash fishes, spoiled items should be avoided.
6. Install feeding trays for sinking feed and feeding rings for floating rings to reduce feed wastage.
7. Prepare feeding schedule to avoid over feeding. Feeding frequency should not be exceeded beyond three times.
8. Regularly assess the water quality and quantity of fishes stocked in the system and their weight for calculating the exact feed requirement.
9. Do not overfeed if the fishes are not consuming feed.
10. Grading of fishes is important at regular intervals.

Conclusion

Effective feed management plays a crucial role in ensuring optimal feed efficiency and minimizing wastage. Using freshly prepared, high-quality feed with proven feed conversion ratios (FCR) can significantly reduce feed loss. Feeds that lack water stability, have degraded in nutritional quality, or are poorly consumed by fish or shrimp should be avoided. Feed particle size must be tailored to suit the specific life stage of the cultured species. Ration quantities and feeding schedules should be adjusted based on standard feeding guidelines, fish feeding behaviour, and prevailing environmental conditions (ICAR – CIBA Training Manual 2021,2022).

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HERBAL INFUSION IN PROCESSED FOODS

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Abstract

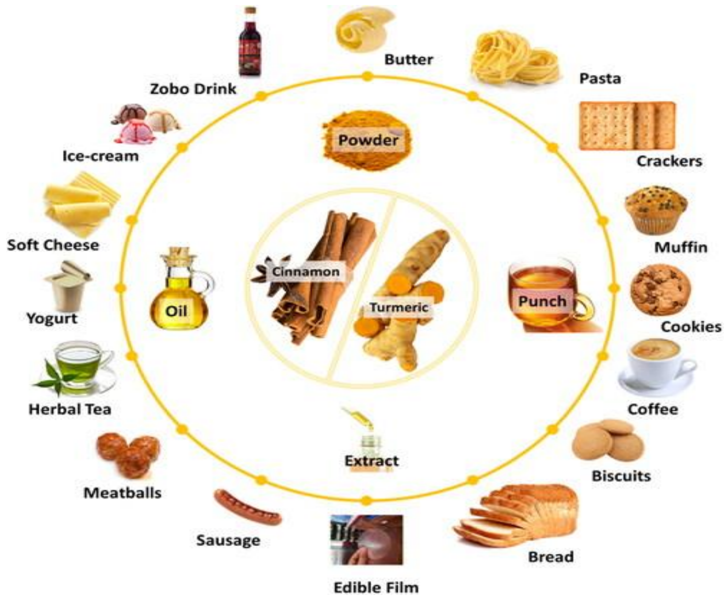
As consumers increasingly demand healthier, functional, and clean-label foods, herbal infusions are emerging as valuable additions to processed food formulations. Derived from spices, roots, and leaves, herbs like cinnamon, turmeric, and herbal teas offer a rich source of bioactive compounds such as polyphenols, flavonoids, and essential oils. These compounds exhibit antioxidant, antimicrobial, and anti-inflammatory properties, contributing to improved shelf life, sensory quality, and nutritional value. Herbal infusions have found applications across diverse food categories including dairy, bakery, beverages, meat products, and even edible films. Products such as cinnamon yogurt, turmeric ice cream, herbal breads, zobo drink, and infused sausages exemplify the integration of traditional botanical ingredients with modern food systems. However, challenges such as thermal degradation, flavor compatibility, and regulatory constraints must be addressed through advanced formulation techniques like encapsulation and controlled release systems. Despite these hurdles, herbal infusions align well with current consumer trends focused on natural, wellness-oriented diets. This review highlights the functional potential, technological considerations, and market implications of herbal-infused processed foods, underscoring their role in shaping the future of health-focused food innovation.

Keywords : Functional food, herbal infusion, bioactive compounds, natural preservatives, Food innovation, encapsulation.

Introduction

As consumer demand shifts toward healthier and more functional food products, the global food industry is increasingly exploring the use of plant-based ingredients to enhance nutritional value and extend shelf life. Herbal infusions—derived from spices, roots, and leaves—are gaining prominence in processed food formulations due to their wide range of bioactive compounds. These herbal components offer several health benefits, including antioxidant, antimicrobial, anti-inflammatory, and metabolic regulatory effects. Among the most notable are cinnamon, turmeric, and herbal teas, which are now being infused into everything from beverages and dairy to baked goods and meat products.

The visual illustration provided highlights the broad scope of herbal infusion across processed food categories. Products such as yogurt, ice cream, bread, biscuits, coffee, sausage, and meatballs are being enhanced with herbal powders, extracts, or oils. Not only do these infusions offer health-promoting properties, but they also introduce natural colors, aromatic flavors, and functional shelf-life improvements—aligning with the modern consumer's preference for clean-label, minimally processed foods.



Functional Compounds in Herbal Ingredients

Herbal infusions typically draw their functional potency from phytochemicals such as polyphenols, flavonoids, terpenes, and essential oils. These compounds have demonstrated bioactivity against oxidative stress, inflammation, and microbial growth, making them ideal for use in food preservation and enhancement.

Cinnamon, for instance, contains cinnamaldehyde, eugenol, and coumarin, which not only contribute to its signature aroma but also offer antimicrobial and antioxidant activities. Studies have shown that cinnamon can inhibit the growth of *E. coli*, *Listeria monocytogenes*, and various fungi, making it a suitable natural preservative in bakery and dairy applications.

Turmeric, widely known for its active compound curcumin, is a vibrant yellow spice with potent anti-inflammatory and antioxidant effects. It has been traditionally used in Ayurvedic medicine and is now being investigated for its roles in metabolic regulation, gut health, and even neuroprotection. However, curcumin's low bioavailability in the human body necessitates formulation strategies, such as nanoencapsulation or combination with black pepper extract (piperine), to enhance its absorption.

Herbal teas, including infusions from chamomile, peppermint, hibiscus, and green tea leaves, provide a range of polyphenols and flavonoids. These compounds are associated with cardiovascular benefits, digestive support, and mood regulation. As water-soluble extracts, herbal teas are ideal for incorporation into beverages and sauces, and increasingly into powdered drink mixes and functional dairy products.

Applications in Dairy and Frozen Desserts

Dairy products are an excellent vehicle for delivering herbal bioactives due to their widespread consumption and favorable matrix for flavor and nutrient retention. Products like yogurt and soft cheeses have been successfully infused with turmeric and cinnamon extracts. These not only enhance the antioxidant capacity of the dairy but also contribute appealing color and flavor. Cinnamon-infused yogurt offers a mildly sweet-spicy note and additional antimicrobial properties that may prolong shelf life.

Ice cream, another dairy-based category, has embraced turmeric infusions for their natural color and health halo. Turmeric-infused “golden milk” ice cream has appeared in health-focused food markets, leveraging the wellness trend surrounding turmeric lattes. These products provide a fusion of indulgence and functional eating, making them attractive to health-conscious consumers.

Herbal Infusion in Bakery and Cereal Products

Bakery products represent a substantial category for herbal infusion, as dry powders and extracts can be easily incorporated into doughs and batters without compromising texture. The image provided shows examples such as bread, biscuits, cookies, muffins, and crackers, all of which can accommodate herbal powders like cinnamon or turmeric.

Cinnamon, traditionally used in sweet baked goods such as cinnamon rolls, snickerdoodle cookies, and spice muffins, also imparts antimicrobial benefits that may reduce the risk of mold formation. Its flavor profile aligns well with sugary, buttery baked items, making it a popular choice both for functionality and consumer appeal.

Turmeric, though less commonly associated with sweets, is increasingly being used in savory breads and crackers, where its earthy flavor and vibrant yellow color are perceived as both exotic and healthful. Products like turmeric flatbread or turmeric-infused sourdough highlight the spice’s crossover potential from culinary tradition to commercial formulation.

Beverage Innovations with Herbal Additives

Beverages are one of the earliest and most natural formats for herbal infusion. As seen in the image, herbal tea, coffee, zobo drink, and punch are all being enhanced with botanical extracts to meet growing demand for wellness drinks.

Herbal teas themselves are direct infusions of herbs and serve both as traditional beverages and as ingredients in new product development. For example, cold-brewed herbal teas or sparkling herbal infusions are growing in popularity, especially those featuring ingredients like hibiscus, lemongrass, or ginger.

Zobo drink, traditionally made from hibiscus petals, often incorporates cinnamon and other spices to enrich flavor and health benefits. Cinnamon enhances both the antioxidant potential and aromatic profile of the beverage, making it more palatable and functional.

Coffee is also being reinvented with the addition of cinnamon, turmeric, and mushroom extracts. These additions aim to provide a functional boost to the daily caffeine ritual. Turmeric lattes, or "golden milk," blend turmeric with milk and black pepper and are marketed as calming, anti-inflammatory alternatives to coffee.

Processed Meat and Edible Film Applications

Herbal infusions in meat products serve dual purposes: flavor enhancement and preservation. Products like sausages and meatballs are often vulnerable to lipid oxidation and microbial spoilage. Incorporating herbal oils or powdered extracts can help extend shelf life naturally.

Cinnamon and turmeric have both shown effectiveness in reducing microbial load and delaying rancidity in meat matrices. Moreover, they contribute to distinctive flavors that may help producers differentiate products in a saturated market.

One innovative application is the use of herbal edible films—thin, consumable coatings made from proteins or polysaccharides infused with essential oils or plant extracts. These films can be applied to meat, cheese, or even produce to inhibit microbial growth and preserve freshness. Edible films infused with cinnamon oil or turmeric extract act as natural preservatives while maintaining product quality and edibility.

Challenges and Technological Considerations

Despite the promising benefits, incorporating herbal infusions into processed foods presents several challenges. One of the major issues is thermal stability. Many bioactive compounds degrade when exposed to high temperatures used in baking, pasteurization, or extrusion. This degradation can reduce the efficacy of the herbal ingredient and alter flavor.

Another concern is flavor compatibility. Herbs and spices like turmeric and cinnamon have strong, distinctive tastes that may not be compatible with all food systems or may require careful balancing with other flavors. Overuse can lead to bitterness or off-notes, reducing consumer acceptability.

Moreover, regulatory frameworks in various countries dictate acceptable inclusion levels for herbal extracts, especially those with potent bioactives. For example, coumarin, naturally present in some cinnamon species, has limits in food products due to its potential toxicity at high doses.

Formulators must also consider delivery systems that protect bioactive compounds and control their release. These include microencapsulation, emulsification, or using food-grade carriers that improve solubility and stability.

Consumer Trends and Market Acceptance

Consumer interest in natural and functional foods continues to grow, driven by a desire for preventive health, immune support, and clean-label products. Herbal-infused foods align with these preferences and offer a sense of authenticity and tradition, often associated with cultural or historical wellness practices.

Products like turmeric bread, cinnamon yogurt, and herbal tea-infused beverages have successfully entered mainstream and niche markets alike. The combination of visual appeal (e.g., turmeric's golden color), sensory enhancement, and perceived health benefits makes these products particularly attractive.

The image summary also reflects a holistic product innovation approach where herbal infusions transcend individual categories and become a unifying trend across food groups. This diversification allows producers to meet varying consumer needs while promoting a consistent health message.

Conclusion

Herbal infusions represent a promising strategy for enhancing the functional and sensory qualities of processed foods. As illustrated, herbs like cinnamon and turmeric are being incorporated into a wide array of products—from dairy and baked goods to beverages, meat, and even edible packaging. While technical and regulatory challenges persist, advancements in food processing and formulation technologies are enabling safer, more effective, and more appealing use of herbal ingredients.

The integration of traditional botanical knowledge with modern food science not only improves nutritional profiles but also taps into growing consumer interest in natural health solutions. As the food industry continues to prioritize health, sustainability, and innovation, herbal infusions are likely to play an increasingly central role in the future of processed foods.

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MECHANIZATION OF POTATO FARMING

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JOURNEY OF POTATO CULTIVATION IN INDIA

India, known for its diverse agriculture, holds a prominent position in potato cultivation. This article explores the regions suitable for potato farming, the challenges faced by farmers, the emergence of processing varieties, mechanization of potato farming, and the future prospects of this essential crop. Potato cultivation in India is concentrated in the Indo Gangetic Plains, specifically Uttar Pradesh, Bihar, and West Bengal, which contribute to around 85% of the country's production. These regions offer fertile soils and easy access to irrigation, making them ideal for potato growth. However, the short winter duration poses a challenge for maximizing yields. In hilly regions, farmers practice double cropping, allowing them to achieve two potato harvests per year. This involves kharif cultivation during the rainy season and Rabi cultivation in winter. Planting occurs between July and November for kharif, and February to June for Rabi While some parts of India use drip irrigation, the majority of locations rely on the furrow-irrigated raised-bed system for potato farming.

India predominantly grows domesticallydeveloped potato varieties, often using CIP lines as one parent. Popularvarieties include Kufri Jyoti, Kufri Pukhraj, Kufri Bahar, Kufri Himalini, andKufri Chandramukhi. However, private companies also introduce foreignvarieties to the Indian market Potato preferences vary by region in India. Thenorthern regions favor yellow/white-skinned potatoes, while the eastern regions prefer red-skinned ones. Whitish yellow flesh is widely used, butthere is a rising demand for purple- skinned potatoes due to their high antioxidant content With theWesternization of diets, there is an increasing demand for processedpotato products such as chips and french fries. India has responded bycultivating specific processing varieties like Lady Rosetta, Chipsona 1-4, and Kufri Frysona. Indian potato breeders are focusing on developing short- duration, early maturing varieties with high yields, particularly for processing purposes. Climate resilience, heat and drought tolerance, and biofortified varieties are also part of their agenda. Potato farmers in India face challengesin accessing quality seeds at affordableprices, marketing their produce, and combating pests and diseases. Croprotation with other crops like rice and wheat is common, and mechanization in planting, care, and harvesting is gradually spreading among farmers. After harvest, farmers sell their potatoes to traders or local markets. Large-scalefarmers utilize cold storage facilities to store their produce for future sale. These facilities can store up to 5,000 tons or more of potatoes for up to 10 months. Despite the challenges, the future of potato cultivation in India

looks promising. With the development of processing varieties and the increasing demand for diverse potato products, there are opportunities for growth. The collective efforts of potato breeders andsmall farmers aim to ensure a fruitful future for this beloved tuber in India. Potato is one of the world's most important non-cereal, high yielding horticultural food crops which is native of Peru-Bolivia in the Andes (South America) and seems to have been introduced in India from Europe by Portuguese in the early 17th century.it has been revealed, that, according toFAO, Potato is consumed by more thanone billion people the world over.it is a high quality vegetable cum food crop and used in preparing more than 100 types of recipes in India. Popular Indian recipes like samosas and alu parothasare prepared from potatoes. The proteinof potato has more biological value thanprotein of cereals and better than milk. The biological value of mix of egg and potato is higher than egg alone. Hence potato can be supplementof milk and meat taste for improving their taste, lowering energy intake and reducing food cost.

POTATO PLANTER

Potato planters are versatile implements that you can attach to yourtractor to plant potatoes. It can ditch, fertilise, compact the soil. It is an advanced precision potato planter with class-leading features and technology to suit the needs of every Indian potato farmer. It is designed and developed in collaboration with the European-based Dewulf to make your potato farming operations more efficient, produce higher potato yields, and reduce operational costs.

FEATURES OF THE POTATOPLANTER

The potato planter's moving floor ensures that the potato seeds are consistently supplied to the planting beltwithout blockages The adjustableridges create the proper compaction of the soil for optimum air and sunlight forthe potato seeds. It comes with a variety of holding cups-shaped like human hands that avoid double-planting or missed seeds while planting, and you can get those from 20 mm to 60 mm, depending on your seed size.

The hold cups are driven by a mechanical belt vibration that enhancessingulation. You can opt for fertilisertanks of 130 litres (65 litres + 65 litres) that can administer fertiliser at the rightheight without damaging the seeds. The planter offers multiple planting solutions, including zig-zag or straight planting, with or without fertiliser, and whole or cut potatoes. The height- adjustable shaft, depth head, and furrow opener, along with tractor's hydraulics, ensure that the seedlings are planted at a consistent height throughout the farm. The adjustable rowwidth allows you to configure the planter to suit your farm.

WORKING

It is an ingenious farming implementthat makes your farming easier, and itsworking is relatively easy to understand.The process begins in the potatohopper that can hold up to 500 kg of seeds. From the hopper, the potatoes move to the moving floor that ensures that the potato seeds are fed to the beltconsistently and smoothly.

From there, the seeds are picked up byhand-shaped holding cups driven byvibrating mechanical belts, ensuring optimum singulation of the seeds withinthe cups. From there, the seeds are dropped into the ditches formed by the planter's blades. The precision planter ensures the seeds are dropped at the right height and location. Then, the compactor compacts the soil while the ditches are closed with another set of blades. This ensures that the soil is notover or under-compressed, ensuring anoptimum environment for the soil.

BENEFITS OF A POTATO PLANTER

It increases potato yield by 25%. It ensures accurate and high-speedplanting, covering 4000 m2/h. Enhanced singulation means there are no missed spots in the ditches and no double planting that may affect the growth.

It saves time and effort as it is quicker and you don't have to rely on manual labour for farming. It ensures properdepth and distance between the potatoseeds, so each plant gets enough nutrition and grows into a healthy yield.It is easy to manage and control, and itcan be configured to your farm as per your preferences.

ROBOSPRAY

Robo spray is revolutionary way of spraying that liberates farmers and farm lands from the traditional, unsustainablemethod of broadcasting. leverages realtime Artificial intelligence assisted computer vision to selectively spray chemicals on plant foliage with an accuracy of 99.8%. This kind of smart, targeted spraying on plants reduces chemical usage by up to 90% and limitsthe environmental impact of excessive spraying on soil. The use of robospray makes seasonal spraying taskseffortless and efficient for farmers. The 90% chemical reduction is a direct inputcost saving for the farmer. In the long run, farmers benefit when their soil is safeguarded from unwanted chemical exposure preserving its nutrition for future generations to grow. it can also be used to deliver precision dosage of liquid fertilizers to crops. This kind of plant level care can enable farmers to reap maximum benefits.

Break Free from Broadcast Spraying: World over farmers rely on the unsustainable method of broadcastspraying either through machines or human knapsack spraying. Broadcast spraying is both unscientific and inconsistent resulting in over or underspraying of chemicals. Under spraying leads to decreased crop protection andover spraying compromises soil integrity, food safety and causes groundwater contamination. Broadcast spraying carried out by human knapsack sprayers put their health atextreme peril. For farmers, it drives upchemical costs and depletes soil nutrition in the long run.

POTATO HARVESTER

SELF PROPELLED POTATOCOMBINE HARVESTOR

Introduction

The self-propelled machine for combined potato harvesting is composed of a crawler chassis, a digging and lifting device, a potato– plastic-film separation device, acirculating and lifting device, a manual sorting platform, a residual-film collecting and bundling device, a ton- bag handling device, a transmission system, a hydraulic control system, anda frame. Its size and configuration meetthe agronomic requirements of the potato planting mode on large ridges with two rows per ridge and plastic film mulch covered with soil. The machine employs a crawler chassis suitable for potato harvesting in small and medium plots that is able to perform tight turns and limit soil compaction duringoperations.

Working

During operation, the profiling crushing roller of the digging and lifting device crushes the soil clods on the surface ofthe film and limits the digging depth of the machine, while the earth-cutting disc cuts the soil clods, vines, and weeds to prevent congestion and entanglement at the front end of the digging and lifting device. The digging shovel picks up the plastic film and potato mixture and transports it to the potato–plastic-film separation devicevia the lifting chain. The potato and soilare initially separated, and some soil pieces and debris are sieved off through the gaps in the lifting-chain bars through shaking and loosening. The potato– plastic-film separation device separatesthe plastic film from the potato tubers and further crushes and sieves off the large soil pieces. The plastic film is transported to the collecting device for rolling and bundling, while the potato and soil pieces that cannot pass through the gaps of the conveying chainrod fall into the circulating and lifting device. This further separates the potatoes from the soil pieces and lifts them to the manual sorting platform,where the unscreened soil pieces are screened out by hand by two to four operators. The conveyor screen transports the potatoes backward to theton bag for collection, and the ton-bag handling device unloads the bag full of potatoes to the ground.

Item	Parameter Values
Length × width × height (mm)	6050 × 2150 × 2500
Body style	Self-propelled crawler
Track gauge (mm)	1250
Engine power (kW)	75
Harvesting ridges	1
Operating rows	2
Working width (mm)	1100
Range of digging depths (mm)	0 to 300
Operating speed *v* (m/s)	0.4 to 0.8

Benefits

Compared with other equipment withsimilar functions, the self-propelled machine for combined potato harvesting and residual plastic film retrieval performs better in separating potatoes from debris and plastic filmand has a higher production efficiency of 0.12 ha/h.

Tractor mounted potato harvester

Introduction

Harvesting procedures with continuousoverloading are particular efficient. The2-row automatic elevator harvester SGPH-200 is a high-performancepotato harvester with maximum cropprotection & capable to save on labour cost. The straight crop flow, minimaldrop steps and compact design are themost important arguments for this harvester. In addition, the open design of the main frame with Lug conveyer offers a very good view across the entire machine. The machine can be adapted to all harvesting conditions. This Innovative technology is particularly gentle to the crop, even under the most difficult soil conditions. For haulm separation, the machine is equipped with a haulm separator roller,a lug conveyer web. The length and flexibility of the cart elevator ensure a smooth and gentle discharge of the crop even into mid-size trailers. SGPH-200 have hydraulic steerable wheels asstandard which ensures minimumturning radius of 5.2 Metre.

Advantages

Adaptive for small size farm land (avg
2.5 acre) Requirement of tractor with 50Hp 4wd only. Excellent visibility of potato flow throughout the harvester. Gentle transport of the crop without anyfriction. The compact design and proven, reliable technology. Compactdesigned potato harvester with high speed of efficiency. Ability to reducelabour requirement significant.

Working

Digging system: The system comprisesa digging share . blade, fixed in front ofthe elevator and attached to its frameset to cut beneath the lowest potatoes. It consists of two HC steel blades of triangular shape with side discs and a central set of discs,supported with the main frame. The width of each blade is kept as 400 mm and blade to blade spacing is kept as 600 mm, thus making the prototype suitable to harvest crop planted at 600 mm row spacing. The blades aresupported from their lower surface withthe main frame with 50 √ 25mm size curved supports. The stone deflectors system is provided behind the digging blades. Diabolo rollers were provided over and in front of blades to reduce theformation of clods during harvesting in heavy soils, which facilitates better separation and avoid injury to the tubersfrom soil clods.

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Elevator conveyor

The elevator conveyor is rod chain typeof length of 5200 mm and consisting of135 rods. It is made of 12 mm diameterMS rods with end pressed, drilled and fitted at a spacing of 30 mm from adjacent rods on the 50 mm × 4 ply rubber belt from both sides and also at the centre. The rod chain is supported from the rear with drive supports and from the front with digger pulleys. Two numbers of agitator sets are provided below the chain .

POTATO PROCESSING EQUIPMENTS

The potato processing industry encompasses various activities, including cleaning, peeling, cutting, blanching, frying, freezing, and packaging.

Scope of Potato Processing Industry

The potato processing industry is thriving, and it's going through a time ofexpansion, thanks to rising global demand for vegetarian foods, the growth of the hospitality business, hoteldining, the growth of the processed foodindustry, and customer desire for higherquality and sustainability. Globally, the processed food industry sector is worth more than 2.2 trillion dollars, with over 420,000 enterprises.

PepsiCo was inspired by the product's commercial success and consumerapproval to build more processingfacilities for Potato Chips, which prompted a few more domestic companies to follow suit.

After that, McCain, a Canadian company, opened their plant in 2008, and HyFun Foods opened its first processing plant in Gujarat in 2015 to produce frozen French fries and potatospecialties.

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State	Area (in ·000 ha)	Production (in ·000 tonnes)
Assam	104.07	1039.27
Bihar	319.13	6345.52
Gujarat	112.40	3549.38
Madhya Pradesh	141.05	3161.00
Punjab	92.36	2385.26
Uttar Pradesh	608.84	13870.73
West Bengal	427	8427
Total*	2124.41	43882.59

Source: Ministry of agriculture, I[st] advance estimates for 2016-2017 [6]
* includes all other states

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MICRO-PLASTICS IN FISH: AN EMERGING ENVIRONMENTAL AND FOOD SAFETY THREAT

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Abstract
Micro plastics (MPs), plastic fragments smaller than 5mm, have become a major environmental contaminant, infiltrating marine and freshwater ecosystems. In India, the increasing presence of MPs in commercially important fish species raises concerns about food safety and ecosystem health. This article reviews recent studies on the occurrence of micro plastics in Indian fisheries, their potential sources, and the implications for human consumption.

Introduction
Plastic pollution is a rising global issue, with India contributing approximately 0.09 to 0.24 million metric tonnes of plastic waste to the ocean annually. A significant proportion of this waste degrades into micro plastics, which enter aquatic food chains and accumulate in marine organisms, including fish. The rising global use of plastic has led to the alarming spread of **microplastic pollution.** Defined as plastic particles smaller than 5 mm, micro plastics have been found in oceans worldwide, infiltrating **marine life** including fish, mollusks, and even fishmeal, a key component of aquaculture and livestock feed. The main concern surrounding micro plastics pollution is their ingestion and entanglement inside the organs of marine biota causing suffocation and their eventual death. Micro plastics have been reported in the gastrointestinal tract (GIT). But since GIT is removed most of the time before human consumption, micro plastics in fishes were not considered as a major food safety issue until recently. These micro plastics pose a serious threat to aquatic organisms, particularly fish, and indirectly to humans through **bioaccumulation and biomagnification.** Given India's status as the second-largest fish producer in the world, the presence of micro plastics in fish has serious implications for food security and public health. Micro plastics have been reported in pelagic environments across the world and are predicted to be doubled by 2030.

Sources of Micro plastics in Indian Aquatic Ecosystems
Micro plastics originate from various primary and secondary sources such as: Industrial and Urban Runoff, wastewater discharge carries synthetic fibers from textiles, cosmetics, and packaging industries into rivers and coastal waters. Fisheries and aquaculture is also another reason as abandoned fishing gear, nets, and plastic feed packaging contribute to marine MP pollution. Household waste, plastic bags, bottles, and packaging material degrade into MPs and enter aquatic ecosystems. Riverine inputs major Indian rivers such as the Ganges and Yamuna act as pathways, transporting MPs from inland areas to marine environments.

Micro plastics can be categorized into:

- **Primary micro plastics**: Intentionally manufactured small plastics (e.g., microbeads in cosmetics).

- **Secondary micro plastics**: Result from the breakdown of larger plastic items like bags, bottles, and fishing gear.

Occurrence of Micro plastics in Fish from Indian Waters

Recent studies have detected micro plastics in commercially important fish species along the Indian coastline. A study conducted in Kerala found MPs in 7% of edible fish tissues and 41.1% in inedible tissues. Similarly, research from Tuticorin, Tamil Nadu detected MPs in 30% of the fish analysed, with microfibers being the most common type. Micro plastics have been detected in both pelagic (surface-dwelling) and demersal (bottom-dwelling) fish species, suggesting wide-scale contamination across different trophic levels.

Health and Environmental Implications

Impact on Fish and Marine Life**,** MPs accumulate in the gills, intestines, and muscle tissues of fish, potentially affecting their growth, reproduction, and immune function. MPs act as carriers of persistent organic pollutants (POPs) such as pesticides, heavy metals, and industrial chemicals, which further bio-accumulate in the food chain.

Human Health Risks

Studies estimate that Indians consuming fish may ingest 40–45 micro plastics per year. While edible fish fillets contain lower MP concentrations, the risk is higher for consumers of small, whole fish such as anchovies and sardines, which are consumed without gut removal. MPs are linked to endocrine disruption, inflammatory responses, and potential carcinogenic effects due to their ability to leach toxic chemicals. Micro plastics can cause **gut blockage, inflammation, reduced growth and reproduction** in fish. They may also **adsorb toxic chemicals** like Ploychlorinated Biphenlys (PCBs) and Polyclinic Aromatic Hydrocarbons (PAHs), which may leach into fish tissues and be consumed by humans. Although current levels in edible fish tissues are low, the **cumulative effect** through the food chain is a rising concern.

Mitigation Strategies and Policy Recommendations

With the rising threat of micro plastic pollution to aquatic ecosystems and human health, it is crucial to adopt a comprehensive and coordinated approach. Strengthening the Plastic Waste Management Rules to regulate plastic waste can help curb mismanaged disposal and reduce the influx of plastics into the environment. Enforcing a ban on microbeads in cosmetics and personal care products is equally important, as these micro plastics contribute directly to water contamination. Furthermore, improving wastewater treatment systems by upgrading sewage infrastructure can filter micro plastics effectively before discharge into water bodies. In the fisheries sector, promoting sustainable fishing practices, such as encouraging biodegradable fishing gear, can minimize plastic pollution from abandoned fishing equipment. Lastly, public awareness campaigns are essential to educate consumers and industries about reducing single-use plastics and enhancing recycling practices, fostering collective responsibility for a cleaner and healthier environment.

Conclusion

Micro plastics have silently but steadily infiltrated the marine food web, compromising not only oceanic health but also posing serious and far-reaching risks to human health, food security, and ecosystem stability. In India, where seafood forms a vital part of both domestic consumption and global exports, the growing presence of micro plastics in fish demands immediate and coordinated action. The consequences are not limited to environmental degradation alone—they extend to threatening livelihoods, nutrition, and public health at a national scale. Strengthening efforts to monitor, regulate, and reduce plastic pollution must become a priority, integrating scientific research, policy reforms, and public participation. Moreover, dedicated research into the long-term impacts of micro plastic ingestion on human physiology, ecosystem dynamics, and food chain stability is crucial. Future studies should focus on standardized methodologies for micro plastic detection, assessment of bioaccumulation across different trophic levels, the toxicological effects of associated chemical contaminants, and developing innovative mitigation strategies such as biodegradable alternatives and advanced filtration technologies. The choices we make today in combating plastic pollution will ultimately define the future health of our oceans, our economy, and the well-being of generations to come.

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CORRECTING NUTRIENT IMBALANCE IN INDIAN AGRICULTURE

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Abstract

India is facing the challenge of meeting its requirement of fertiliser due to disruption in supply chain and increase in price of fertilisers. Undoubtedly, fertiliser use in India after green revolution increased significantly but it is highly unbalanced. The current status of fertilizer nutrient imbalance in Indian agriculture shows a significant skew in the ratios of nitrogen (N), phosphorus (P), and potassium (K) applied to crops. Correcting nutrient imbalance in Indian agriculture is critically important for enhancing soil fertility, improving crop productivity, and ensuring nutritional security. This paper aims at highlighting the current status of nutrient imbalance and measures to correct this.

Introduction

Correcting nutrient imbalance in Indian agriculture is critically important for enhancing soil fertility, improving crop productivity, and ensuring nutritional security. Imbalances, especially deficiencies in micronutrients like zinc, boron and iron, are widespread due to intensive cropping, alkaline soils, high pH levels, and imbalanced fertilizer use common in regions like Punjab and Haryana. These deficiencies cause significant yield losses (5-30% in major crops), reduce crop quality, and contribute to human malnutrition issues like iron-deficiency anemia and zinc deficiency-related health risks. Balanced nutrient management improves crop yields and quality by replenishing nutrient-depleted soils.

Correcting imbalances involves strategies such as balanced fertilizer application (including micronutrient-enriched fertilizers), soil amendments to adjust pH, foliar sprays, biofortification (breeding nutrient-rich crops), and precision agriculture techniques that optimize nutrient use efficiently. These approaches also contribute to sustainable agricultural practices and environmental protection by reducing excess or inefficient fertilizer use.

Policy initiatives like India’s Soil Health Card Scheme and Nutrient Based Subsidy aim to support farmers in adopting balanced fertilization practices, as lack of awareness remains a challenge among farmers who often neglect micronutrients, focusing only on macronutrients.

In summary, correcting nutrient imbalances is essential to:

- Prevent crop yield and quality losses.
- Improve human nutrition by enhancing micronutrient content in food crops.
- Promote sustainable farming and soil health.
- Support national food security and agricultural resilience.

Failure to address these imbalances risks continued productivity decline, food insecurity, and public health challenges in India.

Current status of fertilizers nutrient imbalance in Indian Agriculture

The current status of fertilizer nutrient imbalance in Indian agriculture shows a significant skew in the ratios of nitrogen (N), phosphorus (P), and potassium (K) applied to crops. India's actual NPK ratio as of Kharif 2024 is about 9.8:3.7:1, which deviates sharply from the recommended balanced ratio of 4:2:1. This imbalance is primarily due to excessive use of nitrogenous fertilizers, especially urea, and insufficient use of phosphatic and potassic fertilizers. This leads to nutrient deficiencies in soil, soil degradation, and reduced crop yields.

Key reasons for this imbalance include

- Heavy subsidies on urea (nitrogenous fertilizer), making it much cheaper than phosphorus and potassium fertilizers, causing farmers to overuse nitrogen.
- High prices and import dependency (especially on potash, nearly fully imported) discourage balanced fertilizer use.
- Lack of farmer awareness about balanced nutrient needs, often equating lush greenery from nitrogen with productivity, ignoring phosphorus and potassium requirements.
- Poor implementation of soil testing and nutrient recommendations further exacerbates imbalanced fertilizer use.
- Recent data show the NPK imbalance has worsened over decades; the NPK ratio moved from about 5.9:2.4:1 in 1991-92 to around 11.8:4.6:1 in 2022-23, indicating even greater skew towards nitrogen.
- Although policy reforms such as Nutrient-Based Subsidy schemes and promotion of nano-urea and biofertilizers aim to address these issues, the subsidy allocation still favours urea heavily (around 75% of fertilizer subsidies go to urea), which tends to perpetuate imbalance.

Soil nutrient deficiencies remain widespread in India: less than 5% of soils have adequate nitrogen, about 60% are deficient in phosphorus, and 32% in potash. Micronutrient and organic carbon deficiencies also impact soil health severely. In summary, India continues to face a serious fertilizer nutrient imbalance problem characterized by overuse of nitrogen relative to phosphorus and potassium, causing soil degradation and productivity concerns. Efforts by government policies are ongoing but challenges remain due to subsidy structures, import dependence, and farmer practices.

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Impact of fertilizer imbalance on soil health

The impact of fertilizer nutrient imbalance on soil health in Indian agriculture is significant and multifaceted:

- Soil Acidification: Excessive use of nitrogenous fertilizers, especially urea, causes soil acidification by releasing hydrogen ions, which lower soil pH. This acidification depletes essential base cations like calcium and magnesium and can release toxic aluminium ions, harming plant nutrient uptake and soil microbial functions.
- Loss of Soil Organic Matter (SOM): Over-application of nitrogen accelerates decomposition of soil organic matter, reducing soil organic carbon. This diminishes soil fertility, water retention, and structure, negatively affecting long-term productivity.
- Reduced Microbial Diversity and Activity: Imbalanced fertilization disrupts microbial communities vital for nutrient cycling and soil health. Particularly, excess nitrogen can reduce beneficial mycorrhizal fungi, weakening nutrient uptake and soil biological activity.
- Compromised Soil Structure: Accumulation of mineral salts from overuse of chemical fertilizers leads to compaction, erosion, reduced water retention, and nutrient leaching, further degrading soil quality.
- Nutrient Deficiencies and Crop Stress: Skewed nitrogen use limits availability of phosphorus, potassium, and micronutrients, weakening plant resistance to diseases and environmental stresses, which reduces crop yield quality and quantity.
- Environmental and Human Health Hazards: Excess nitrogen leaches into groundwater causing nitrate contamination, posing risks like methemoglobinemia and contributing to greenhouse gas emissions such as nitrous oxide.

Efforts to apply fertilizers in balanced proportions alongside organic manures, adopting site-specific nutrient management, and reducing excessive nitrogen inputs can help restore and maintain soil health while sustaining crop yields.

In summary, fertilizer imbalance—primarily excess nitrogen relative to phosphorus and potassium—degrades Indian soils through acidification, organic matter loss, microbial disruption, and structural damage, highlighting the need for balanced fertilization policies and practices.

Soil acidification from excess nitrogen

Soil acidification from excess nitrogen primarily results from the nitrification process when ammonium-based fertilizers (like urea and ammonium sulphate) convert to nitrate in soil. This conversion releases hydrogen ions (H^+), lowering soil pH and causing acidification. Acidification is especially pronounced when nitrate is leached away rather than taken up by plants, as leaching removes base cations that buffer acidity, further lowering pH.

Key points on soil acidification from excess nitrogen:

- Nitrogen form matters: Ammonium-based fertilizers acidify soil more since nitrification produces two H+ ions per ammonium molecule. Nitrate-based fertilizers are less acidifying or can even raise pH slightly upon plant uptake.
- Excess nitrogen input: Applying nitrogen beyond crop needs causes accumulation of acidity, accelerating acidification.
- Soil acid buffering capacity: Soils with low buffering capacity (low organic matter, certain parent materials) acidify faster under excess nitrogen.
- Consequences: Acidification depletes base cations like calcium and magnesium, increases toxic aluminum availability, harms microbial communities, reduces enzyme activity, and degrades soil health and productivity.
- Mitigation: Strategies include optimizing nitrogen rate and form, enhancing soil buffering with lime or alkaline amendments, and integrated nutrient management balancing acid production and buffering.

In India's context with heavy use of nitrogenous fertilizers like urea, this mechanism likely contributes significantly to observed soil acidification problems, soil degradation, and nutrient imbalances.

In summary, excess nitrogen fertilizer—especially ammonium forms—promotes soil acidification via H+ generation in nitrification, impacting soil chemistry, biology, and crop health, necessitating balanced fertilization and soil management strategies.

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Reduced Microbial Diversity and Activity: Imbalanced fertilization disrupts microbial communities vital for nutrient cycling and soil health. Particularly, excess nitrogen can reduce beneficial mycorrhizal fungi, weakening nutrient uptake and soil biological activity.

Compromised Soil Structure: Accumulation of mineral salts from overuse of chemical fertilizers leads to compaction, erosion, reduced water retention, and nutrient leaching, further degrading soil quality.

Nutrient Deficiencies and Crop Stress: Skewed nitrogen use limits availability of phosphorus, potassium, and micronutrients, weakening plant resistance to diseases and environmental stresses, which reduces crop yield quality and quantity.

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In summary, fertilizer imbalance-primarily excess nitrogen relative to phosphorus and potassium-degrades Indian soils through acidification, organic matter loss, microbial disruption, and structural damage, highlighting the need for balanced fertilization policies and practices. Soil acidification from excess nitrogen. Excess nitrogen fertilizer-especially ammonium forms-promotes soil acidification via H+ generation in nitrification, impacting soil chemistry, biology, and crop health, necessitating balanced fertilization and soil management strategies.

Nitrogen fertilizer alternatives for sustainability: Fixing nitrogen for a better climate

Alternative approaches: Synthetic Fertilizer Alternatives for Farmers and Gardeners

Environmentally friendly fertilizers: Sustainable alternatives to nitrogen fertilizers focus on reducing environmental impact, improving soil health, and enhancing nutrient use efficiency.

Key alternatives include:

Biological nitrogen fixation: Using legumes (peas, beans, lentils) with nitrogen-fixing bacteria (rhizobia) helps convert atmospheric nitrogen into plant-available forms naturally. Research is ongoing to extend this to cereals like rice and wheat to reduce synthetic fertilizer dependence.

Biofertilizers: These contain beneficial microbes that promote nitrogen fixation and nutrient uptake, reducing the need for synthetic nitrogen. Examples include Rhizobium, Azotobacter, and mycorrhizal fungi.

Organic fertilizers: Derived from animal manure, compost, plant residues, fish emulsions, blood meal, or seaweed, they improve soil fertility, structure, and microbial activity while supplying nitrogen more sustainably.

Slow-release and controlled-release fertilizers: These release nitrogen gradually, enhancing nutrient use efficiency and reducing losses by leaching or volatilization.

Nano-fertilizers: Using nanotechnology to improve nutrient delivery efficiency, reducing quantity needed and environmental pollution.

Green hydrogen-based fertilizer production: Emerging technologies use renewable electricity to produce hydrogen for ammonia synthesis, lowering carbon emissions compared to fossil fuel-based production, though energy intensive.

Carbon capture and storage (CCS): For traditional nitrogen fertilizer production, CCS can reduce CO2 emissions, but reliance on fossil fuels persists. Government policies promoting integrated nutrient management, organic farming, and research into biological nitrogen fixation and renewable production methods are crucial for long-term sustainability.

In summary, integrating biological nitrogen fixation, biofertilizers, organic inputs, innovative fertilizer formulations, and renewable energy-based production provides promising pathways to sustainable nitrogen fertilizer alternatives that reduce environmental harm and enhance soil health in Indian and global agriculture.

Regional Nutrient Imbalance in Indian Agriculture: A Summary

India’s agriculture faces a serious challenge of regional nutrient imbalance, where some nutrients are overused while others are neglected. This imbalance varies widely across regions due to differences in cropping patterns, irrigation, fertilizer subsidies, and farmers’ awareness.

Key Causes of Nutrient Imbalance

1. Overuse of Nitrogen (N):
   - Due to subsidies on urea, nitrogen is used excessively across most regions.
   - States like Punjab, Haryana, Uttar Pradesh, and Bihar show very high N application, often without adequate phosphorus (P) and potassium (K).

2. Neglect of Potassium (K) and Secondary Nutrients (S, Ca, Mg):
   - Potassium is underused in many regions, especially in rainfed areas.
   - Secondary and micronutrients (like Zinc, Boron, Sulphur) are often ignored due to lack of awareness and higher costs.

3. Unbalanced NPK Ratios:

Ideal N:P:K ratio is 4:2:1, but many states show skewed ratios:
   - Punjab: ~31:8:1
   - Uttar Pradesh: ~17:6:1
   - Tamil Nadu: ~7:2:1

- West Bengal: better balance at ~3.3:2.1:1
- Soil Nutrient Mining: Intensive cropping in states like Punjab, Haryana, and Andhra Pradesh leads to mining of nutrients from soil without proper replenishment.
- Low Organic Matter Use: Decline in use of farmyard manure, compost, and green manures reduces soil health and microbial activity.

Region-Wise Highlights

Region Key Issues

- North-West India (Punjab, Haryana) Overuse of N, depletion of soil organic matter, neglect of micronutrients
- Eastern India (Bihar, WB, Odisha) Low total fertilizer use, poor awareness of micronutrients
- Central India (MP, Chhattisgarh) Underuse of fertilizers, emerging deficiency of S and Zn
- South India (AP, TN, Karnataka) Better fertilizer balance, but rising S & Zn deficiencies
- North-East India Low input use, but growing P and K deficiencies as farming intensifies

Consequences of Nutrient Imbalance

- Low productivity and declining soil health
- Environmental issues like water pollution, greenhouse gas emissions
- Increased cost of cultivation due to inefficiency
- Micronutrient deficiencies in crops and human diets

Way Forward

1. Promote Integrated Nutrient Management (INM): Combine chemical, organic, and biofertilizers based on soil test.
2. Encourage Soil Testing and Balanced Fertilization : Regular testing and use of Soil Health Cards to guide application.
3. Reform Fertilizer Subsidy Policy : Encourage balanced use by making P & K more affordable.
4. Promote Site-Specific Nutrient Management (SSNM) : Use ICT tools and mobile apps for precision farming.
5. Awareness and Extension Services : Farmer training on nutrient needs and the long-term effects of imbalance.

Nutrient imbalance effects on human health: Nutrient imbalance, particularly micronutrient deficiencies, can have significant adverse effects on human health. Deficiencies in key nutrients such as iron, vitamin A, zinc, iodine, calcium, magnesium, and folate contribute to a range of health problems, including:

- Anemia: Iron, folate, and vitamin B12 deficiencies cause anemia, leading to fatigue, weakness, dizziness, and reduced work and cognitive performance. This is especially severe in children and pregnant women.
- Impaired Immune Function: Malnutrition weakens the immune system, increasing susceptibility to infections and slowing recovery.
- Developmental and Cognitive Impairments: Deficiencies in iodine, iron, and other micronutrients can cause intellectual impairment, poor growth, and developmental delays in children.
- Vision Problems: Vitamin A deficiency can lead to night blindness, xerophthalmia, and permanent blindness if untreated.

- Bone Disorders: Lack of calcium, vitamin D, and magnesium can cause rickets, osteoporosis, and increase fracture risk.
- Increased Risk of Chronic Diseases: Nutrient imbalances contribute to diabetes, cardiovascular diseases, cancer, and metabolic syndromes.
- Other systemic effects: Symptoms like slow wound healing, hair loss, and muscle weakness may also arise due to various deficiencies.

Overall, nutrient imbalance undermines physical health, cognitive abilities, and quality of life, and contributes to public health burdens, particularly in vulnerable populations such as children and pregnant women. Addressing these imbalances through balanced diets, supplementation, and food fortification is vital for health improvement.

Long-term mineral deficiencies can lead to serious and chronic health conditions affecting multiple body systems. Key long-term effects include:

- Bone disorders: Deficiencies in calcium and vitamin D can cause osteoporosis, rickets, increased fracture risk, and weak bones throughout life.
- Anemia and fatigue: Iron deficiency is a major cause of microcytic hypochromic anemia, resulting in fatigue, weakness, reduced work capacity, and in severe cases, increased maternal mortality.
- Impaired immune function: Zinc deficiency can cause impaired immune responses, slow wound healing, and increased risk of infections.
- Cognitive and developmental impairments: Iodine and iron deficiencies cause intellectual impairment, developmental delays, and poor growth in children; vitamin A deficiency affects vision and infection resistance.
- Cardiovascular and metabolic diseases: Magnesium deficiency has been linked to hypertension, type 2 diabetes, colorectal cancer, and cardiovascular diseases.
- Neurological and muscle issues: Deficiencies of potassium and magnesium can cause muscle weakness, cramps, abnormal heart rhythms, and neurological symptoms.
- Other systemic disorders: Selenium deficiency may lead to cardiomyopathy and arthritis; copper deficiency can cause anemia and neurological problems.

Overall, mineral deficiencies cause chronic diseases, reduced physical and cognitive performance, developmental and behavioral issues, and contribute significantly to morbidity and mortality worldwide. Early prevention through balanced diet, supplementation, and food fortification is critical to avoid these long-term adverse effects.

Mineral absorption in the digestive system is a complex, highly regulated process primarily occurring in the small intestine, where minerals from the diet are taken up into the bloodstream for use by the body. The efficiency of mineral absorption depends on multiple factors related to digestive health, including the condition of the intestinal lining, the presence of digestive enzymes and stomach acid, interactions among minerals, and the presence of enhancing or inhibiting substances in the diet.

Key points about mineral absorption and digestive health are:

- Site and Mechanism: Most mineral absorption happens in the upper small intestine. Minerals like iron, calcium, magnesium, zinc, and others are absorbed through specific transporters on the intestinal cells (enterocytes). For example, iron is reduced at the mucosa from Fe^{3+} to Fe^{2+} and transported by divalent metal transporters, while calcium uptake depends on calcium-binding proteins regulated by vitamin D.

- Role of Digestive Secretions: Hydrochloric acid in the stomach is crucial for breaking down food to release minerals and for converting minerals into absorbable forms. It also helps prevent infections by killing pathogens. Low stomach acid, which can occur due to stress or antacid overuse, impairs mineral absorption, especially calcium and iron.
- Intestinal Health: The small intestine's mucosa has villi and microvilli greatly increasing surface area for absorption. If the intestinal lining is inflamed or damaged (due to conditions like Crohn's disease, celiac disease, or infections), the absorption surface reduces, leading to poor mineral uptake and potential deficiencies.
- Interactions and Antinutrients: Some dietary components inhibit mineral absorption (called antinutrients), such as phytates, oxalates, and excessive intake of competing minerals that share absorption pathways. Conversely, certain vitamins enhance absorption—vitamin C promotes iron absorption, vitamin D supports calcium and magnesium absorption.
- Gut Microbiota: Emerging evidence also links a healthy gut microbiota with improved mineral absorption, possibly through modulation of the intestinal environment and reduction of inflammation.

Practical considerations for digestive health to optimize mineral absorption include:

- Proper chewing and digestion starting in the mouth
- Maintaining adequate stomach acid levels
- Eating smaller, frequent meals to improve absorption efficiency
- Avoiding foods or drinks that inhibit mineral uptake with meals (e.g., coffee, tea)
- Supporting gut health to maintain an intact, functioning mucosa

In summary, mineral absorption depends heavily on digestive health, including adequate digestive secretions, healthy intestinal mucosa, and balanced dietary intake with attention to enhancing and inhibiting factors. Any digestive disorders or poor digestive function can lead to mineral malabsorption, contributing to deficiencies and associated health problems.

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MICRO PLASTICS: INVISIBLE THREATS TO OCEANS, CLIMATE, AND EARTH'S VITAL SYSTEMS

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Abstract

Microplastics—plastic fragments smaller than 5 mm—are now pervasive in marine environments worldwide. While their immediate impacts on marine life are visible, their long-term consequences for oceanic processes, climate regulation, and planetary health are only beginning to be elucidated. This article examines how microplastics disrupt marine ecosystems, impair the biological carbon pump, alter nutrient cycling, and push Earth closer to critical environmental tipping points. It further discusses current international responses and underscores the urgent need for coordinated global action to mitigate plastic pollution.

Introduction

Plastics of all sizes enter the oceans daily, gradually fragmenting into microplastics and nanoplastics that are virtually impossible to remove. These particles have become an entrenched component of marine environments, accumulating from the ocean surface to the deepest trenches. Although images of visibly entangled megafauna and plastic-ingesting seabirds have galvanized public concern, less visible but potentially more severe impacts on planktonic organisms and planetary systems warrant equal attention. The pervasive infiltration of microplastics into marine food webs and geochemical cycles poses a complex, long-term threat to Earth's life-support systems.

The Scale of the Problem

Current estimates indicate that approximately 12 million metric tons of plastic debris enter the ocean annually, subsequently fragmenting into trillions of microplastic particles. Microplastics are now documented throughout the water column, including remote deep-sea habitats such as the Mariana Trench. These particles are ingested by marine organisms across all trophic levels—from plankton to apex predators—facilitating their bioaccumulation and potential biomagnification.

Figure 1: Stomach contents of a dead albatross chick. Image by Chris Jordan via Wikimedia Commons.

Mechanisms of Disruption in Ocean Life

Impact on Plankton and the Biological Carbon Pump

Plankton constitute the foundation of marine food webs and are integral to the ocean's biological carbon pump, which sequesters atmospheric CO_2 into the deep ocean. Microplastics disrupt these processes via multiple mechanisms:

Phytoplankton: Exposure to microplastics reduces photosynthetic efficiency and impairs growth.

Zooplankton: Microplastics lower feeding rates, reproductive success, and survival.

Carbon Transport: Ingested microplastics make zooplankton fecal pellets more buoyant, delaying their descent and diminishing carbon flux to deeper layers.

As Carroll Muffett of the Center for International Environmental Law noted, "*Microplastics truly are omnipresent in these environments… they are affecting marine biota at every trophic scale.*"

Alteration of Microbial Communities and Nutrient Cycling

Microplastics also perturb sedimentary microbial communities, altering critical nitrogen cycling processes, including nitrification and denitrification. Disruption of these microbial functions can exacerbate harmful algal blooms and impact nutrient availability, with cascading effects on higher trophic levels and ecosystem stability.

Contribution to Ocean Deoxygenation

Through their effects on planktonic communities and increased organic matter decomposition, microplastics may contribute to ocean deoxygenation. This reduction in oxygen availability, compounded by global warming, threatens the viability of numerous marine taxa adapted to oxygen-rich habitats.

Microplastics and Planetary Boundaries

Plastic pollution is increasingly recognized within the planetary boundaries framework as a "novel entity," a persistent and poorly reversible stressor. The infiltration of microplastics into the biosphere threatens:

- Biosphere integrity, by undermining marine biodiversity.
- Biogeochemical flows, through altered nutrient cycling.
- Chemical pollution boundaries, by introducing persistent synthetic chemicals.

These systemic risks interact with other anthropogenic pressures such as climate change and ocean acidification, intensifying the threat to Earth system stability.

Challenges of Microplastic Cleanup

Existing mitigation strategies primarily target larger debris, while microplastics remain largely beyond the reach of cleanup technologies. Removal at scale is infeasible due to:

- **Their minuscule size.**
- **Dispersion throughout the water column.**

Risk of collateral damage to marine life during extraction. Consequently, preventative measures are essential to halt further inputs.

International Response: The UN Plastics Treaty

In March 2022, the United Nations Environment Assembly initiated negotiations for a legally binding treaty to address the full life cycle of plastics, including production, design, and waste management.

As of late 2024, negotiations have advanced but have yet to achieve consensus. Key points of contention include:

- **Limits on plastic production.**
- **Scope of enforceable measures.**

Obligations for financial and technical support to developing countries. Environmental advocates stress that only robust, science-based policies—such as capping virgin plastic production and phasing out the most hazardous polymers—will meaningfully reduce microplastic pollution.

Conclusion

Microplastics represent an insidious and escalating threat to ocean health, climate resilience, and the long-term viability of Earth's systems. Their impacts propagate from microscopic plankton to planetary processes, rendering plastic pollution a defining environmental and societal challenge of the 21st century. While international efforts to negotiate a global plastics treaty provide grounds for cautious optimism, the urgency to reduce plastic production and consumption cannot be overstated. As marine microplastics researcher Meredith Seeley observed, "*The plastic that's out there is going to keep fragmenting into smaller and smaller pieces. We've reached this point where we can't really go back.*" Proactive, decisive action is now imperative to safeguard ocean ecosystems and planetary stability.

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MILLETS: PROMISING CROPS FOR NUTRITIONAL SECURITY IN CLIMATE CHANGE SCENARIO

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Abstract
Millets are climate resilient and nutritionally superior crops promising for sustainable crop production in era of climate change. Interest in millets has re-emerged owing to their major role in current scenario and realization of its potential in future agricultural scenario. Millets cultivation got a boost due to promotional campaigns at global level to generate awareness of the role millets can play in alleviating climate change effects and providing superior nutritional quality to marginal and small-scale farmers.

Keywords: Millets, climate change, nutri-cereals

Introduction
Millets are among the oldest cultivated foods, with evidence of their domestication dating back to around 8000 BC. They remain traditional staple crops, especially in the dry regions of India. Belonging to a group of small-grained seeded grasses, millets are classified into **major** such as sorghum and pearl millet and **small millets** like finger millet, foxtail millet, little millet, kodo millet, proso millet, barnyard millet, teff, fonio, and browntop millet. Once known as "coarse cereals," they are now recognised as *nutri-cereals* for their exceptional nutrient density. Millets offer a dual advantage of nutrient-rich grains for human consumption and high quality stover for livestock feed while thriving as climate-resilient crops capable of yielding economically even under extreme and marginal conditions. Millet cultivation supports sustainable agriculture by contributing to food and nutritional security, reducing vulnerability to climate shocks and ensuring stable returns for farmers. They currently account for about 10% of India's food basket, grown on nearly 17 million hectares and producing around 18 million tonnes annually (Rao *et al.*, 2017). Despite significant productivity gains especially in sorghum and pearl millet due to improved varieties and hybrids, the area under millet cultivation has steadily declined. Once a daily staple, millets have been reduced to occasional "health foods," their consumption boosted mainly by recent promotional campaigns. This decline stems largely from the Green Revolution's emphasis on wheat and rice, which shifted consumer preferences and reduced demand for millets. Typically grown in the harshest ecologies characterised by poor soils, high temperatures, low rainfall, and frequent drought-millets are naturally adapted to adverse environments. In the context of climate change, they offer a promising solution to both agrarian and nutritional challenges, thanks to their resilience, low input requirements, and rich nutrient profile (Kumar *et al.*, 2018). These climate-smart crops are well-positioned to ensure food and nutritional security for marginalised and resource-poor populations, making them true "future crops" for a sustainable agricultural system.

Table 1: Millets crops and their cultivation areas in India

Crop	Scientific name	Common name	Cultivation areas
Pearl millet	*Pennisetum glaucum*	Bajra	Rajasthan, Maharashtra, Gujarat, UP and Haryana
Sorghum	*Sorghum bicolor*	Jowar	Maharashtra, Karnatka and Tamilnadu
Little millet	*Panicum sumatrense*	Kutki	M.P, Odisha, Jharkhand and UP
Proso millet	*Panicum miliaceum*	Chena	Northern states of India
Kodo millet	*Paspalum scrobiculatum*	Kodo	Odisha, MP, Karnataka and Tamilnadu
Finger millet	*Eleusine coracana*	Ragi	Karnataka, Rajasthan, Andhra Pradesh and Tamil nadu
Barnyard millet	*Echinochloa frumentacea*	Sawan	Uttarakhand, Tamil nadu, Karnataka, Andhra Pradesh
Foxtail millet	*Setaria italica*	Kakun	Meghalaya, Karnataka, Andhra Pradesh, krnataka and Rajasthan
Teff millet	*Eragrostis tef*	Abyssinian lovegrass	Karnataka
Brown top millet	*Panicum ramose*	Dixie signal grass	Karnataka and Andhra Pradesh

Global and Indian Scenario of Millets

Globally millets production is approximately 97.75 million tonnes with an area of 78.43 m ha. Out of which sorghum and pearl millet comprise of more than 90% of the area and production. Among millets, sorghum and proso millet are most widely cultivated. Total of 16.9 million tonnes of millets are produced from 12.7 m ha area. Countries like Sudan, Nigeria, India, Niger and USA constitute 57% of the area under sorghum and 45% production. India leads globally both in area and production of pearl millet (31.5% and 46.7%, respectively). India, Ethiopia, Nepal, Uganda and Malawi shared 99% of the area and production under finger millet globally. In India, millets are adapted to dryland ecologies of arid and semi-arid tropics where these are cultivated in areas characterized by low to moderate precipitation 200-800 mm rainfall. India is the leading producer and consumer of millets crops. In India, maximum area is under pearl millet about 7.4 m ha followed by sorghum 4.45 m ha and finger millet 1.1 mha. Rajasthan, Maharashtra and Karnataka are the leading states with millet cultivation with share of 35%, 23% and 14% to total millets area.

Nutritional Importance

Owing to their excellent nutrient composition as compared to other cereals millets have been crowned as 'nutri-cereals'. Nutrient composition of different millets is shown in **Table 2.** In general millet contains around 7-12% protein, 2-5% fat, 65-75% carbohydrates and 15-20% dietary fibre. The grains are natural source of high iron, zinc and calcium, easy to digest and the grains contain high proportion of non-starchy polysaccharides which prevent constipation, lowering blood cholesterol and slow release of glucose to the blood during digestion. The grains are rich in essential amino acids such as thiamine, riboflavin, folic acid and niacin. Millet kernel is rich source of phytochemicals and polyphenols. Millets provide antioxidant activity with phytates, polyphenols and tannins. Millets are low in glycaemic index due to slow release of glucose in the blood thereby control problem of diabetes. Their consumption provides health benefits such as relief from celiac disease, weight loss, useful in control of diabetes, anti-cancerous properties, heart friendly, prevention of stomach ulcers, good bone development and repair, reduces cholesterol, anti-allergic properties, cure anaemia and many other health boosting properties. Their consumption keeps away from life style diseases/disorders. Millets have good amount of slow digestible starch (SDS) which prolongs digestion and absorption of carbohydrates and beneficial for management of diseases like diabetes. Recent study has established millets as a potential alternative for fortified rice in study conducted on school children in mid- day meals (Anitha et al. 2019). Millets due to their nutrient rich composition makes them an excellent snacks and main course food. Variety of processed foods can be prepared from millets which have been shown in Table 3.

Sorghum: Principal source of protein, vitamins, energy and minerals especially for populace of semi-arid ecologies. Nutritionally better than rice due to richness in protein, fibre, amino acids like thiamine, riboflavin, folic acid, calcium, phosphorus, iron and β-carotene. Rich in minerals such as potassium, phosphorus, calcium with adequate amounts of iron, zinc and sodium.

Pearl millet: Contains phytochemicals which helps in reducing cholesterol. Relatively high energy among millets. Rich in calcium and unsaturated fats excellent for health. It contains foliate, magnesium, copper, zinc and vitamins E and B complex.

Finger millet: Contains high amount of calcium, proteins, essential amino acids, vitamin A, B and phosphorus. Has high fibre content prevents constipation, high blood pressure and intestinal cancer. The grains are rich in calcium which is around 10 times that of rice or wheat. Best food for diabetics as it controls blood sugar level and hypergycemia.

Foxtail millet: Contains high quantity of protein nearly double the quantity in rice. Considered one of the most easily digestible and non-allergic grains available. Rich in dietary fibre, minerals, calcium, vitamins thereby considered one of the most nutritive food for children and pregnant women. Very effective in controlling blood sugar levels and cholesterol.

Kodo millet: The grains contains high protein, low fat and very high fibre content therefore easy to digest. It contains high amount of lecithin and is very beneficial for strengthening nervous system. Rich in vitamin B especially in niacin, B6 and folic acid. It has good amount of minerals such as calcium, iron, potassium, magnesium and zinc. The grains are gluten free therefore good for gluten-intolerant people. Highly beneficial in high blood pressure, high cholesterol levels and for postmenopausal women with cardiovascular disease.

Barnyard millet: Very good source of dietary fibre with both soluble and insoluble fractions, high source of digestible protein. Has linoleic acid as major fatty acid. Has high degree of retrogradation of amylase which helps in formation of high amount of resistant starch. Very beneficial for patients with cardiovascular and diabetes mellitus diseases. Has gluten free grains thus good food against celiac disease.

Proso millet: High amounts of protein crude fibre, minerals and calcium. Grains are completely gluten free with significant levels of carbohydrates and fatty acids. It has good amount of manganese and is a cheaper source of manganese. High amount of calcium and shown to be beneficial in reducing cholesterol levels of body and heart attacks.

Little millet: It has dietary fibre content of around 38% which is highest among cereals. Rich in all essential minerals, vitamins and good energy source. Suitable as processed food as snacks, baby foods etc.

Table 3: Nutritious Value Added Products of Millets

Millet	Recipe
Sorghum	Annam, Dosa, Ambali, Roti, Samosa, Upma, Sankati, Kesari, Khichdi, Chuduwa, Idli, Pongal, Biscuit, Peda, Kheer, Vermicelli, Cabbage muthias, Pancakes, Sharbat, Gorimetteelu, Lassi, Cake, Bhakarwadi, Halwa, Boondi, Ladoo, Uttapam, Wada, Soup
Pearl millet	Onion muthias, Upma, Roti, Pakoda, Halwa, Pesarattu, Thalipeeth, Khichdi
Finger millet	Onion chapatti, Ladoo, Muruku, Mudde, Pudding, Kheer, Upma, Cake
Foxtail millet	Kheer, Mango rice, Cutlet, Coconut rice, Biryani, Bread, Bisebelle baat
Kodo millet	Upma, Methi rice, Pulao, Coriander rice, Paysum, Adai
Barnyard millet	Cutlet, Maheri, Indiana, Pudina rice, Payasam, Pizza
Proso millet	Rawa idli, Khaja, Burfi, Samosa, Payasam
Little millet	Payasam, Curd rice, musjroom Biryani, Pudina rice, Tomato rice, Roti, Paniyaram, Bhel, Patties, Khakra, Idli, Laddu

Source: ICAR-Indian Institute of Millet Research, Hyderabad (Rao et al. 2016)

Solution to agrarian challenges in climate change

One of the greatest challenges of the twenty-first century is meeting the growing food demand of an ever-expanding human population under the constraints of shrinking cultivable land, increasing frequency of severe abiotic and biotic stresses, low soil fertility in marginal areas, and the limited economic resources of small and marginal farmers. Developing countries face the dual burden of hunger and climate change, which threatens agricultural sustainability and food security. The three major cereals- rice, wheat, and maize-currently provide about 60% of the world's food supply, yet their yields have plateaued despite continued demand growth. Millets have the potential to bridge this gap, as they are traditionally cultivated in marginal areas with low soil fertility, limited rainfall, and minimal farm inputs. They are hardy crops with naturally low susceptibility to pests and diseases. Compared to major cereals, millets exhibit greater tolerance to both abiotic and biotic stresses. Their short life cycle (12–14 weeks) enables them to escape drought and avoid critical stress periods, whereas major cereals often require 20–24 weeks to mature.

Physiologically, millets possess the C_4 photosynthetic pathway, which confers higher photosynthetic efficiency at elevated temperatures, along with nitrogen- and water-use efficiencies 1.5 to 4 times greater than C_3 crops (Sage and Zhu, 2011). They can thrive on a wide range of soils-from shallow, low-fertility profiles to those with pH levels between 4.5 (acidic) and 8.0 (alkaline). In contrast to rice and wheat, millets such as pearl millet and finger millet are less sensitive to salinity and can grow in soils with electrical conductivity of 11–12 dS/m. Water requirements for millets are markedly lower than for major cereals: pearl millet and proso millet need only about 20 cm of rainfall, whereas rice typically requires 120-140 cm. Breeding programmes have produced numerous hybrids, particularly in sorghum and pearl millet, adapted to various agro-ecologies and widely adopted by farmers. Additionally, the rich genetic diversity within millet species offers a broad reservoir of traits for targeted crop improvement. Millets are essential for making India's food basket more climate-resilient. Unlike rice, wheat, and maize—which have the highest global warming potential due to their large carbon-equivalent emissions—millets have relatively low carbon footprints, making them important crops for reducing agriculture's contribution to climate change (Prasad and Staggenborg, 2009).

Conclusion

Millets are promising crops for current and future agriculture where production environments pose a risk due to climate change. Owing to their climate resilience and superior nutritional profile, promoting millet cultivation holds an important place in agriculture especially in marginal areas where these are sole staple crops.

Table 3: *Cultivation conditions for millets

Millet	Soil type	Altitude range (m amsl)	Temperature (°C)	pH	Soil salinity (dS/m)	Rainfall (cm)	Maturity duration (days)
Sorghum	Clay loamy to shallow	Up to 3000	26-30	5.0-8.0	4-6	40-100	90-120
Pearl millet	Loamy soils, shallow soils, clay loam, sandy loam	Up to 2700	30-34 (can grow up to 46)	6.0-7.0 (can grow up to 8.0 pH)	11-12	20-60	60-70
Finger millet	Loam rich to poor	Up to 2300	26-29	4.5-7.5	11-12	50-60	90-120
Little millet	-	Up to 2100		-	-		80-85
Kodo millet	Fertile to marginal	Up to 1500	25-27	-	-	800-1200	100-140
Foxtail millet/Italian millet	Sandy to loamy	Up to 2000	16-25	5.5-7.0	6	30-70	75-90
Barnyard millet	Medium to heavy	Up to 2000	27-33	4.6-7.4	3-5	-	45-70
Prosomillet	Sandy loam, saline, low fertile	1200-3500	20-30	5.5-6.5		20-50	60-90

***Source: Kumar *et al.*, 2018**

Table 2 : Nutrient composition of millets

Millet	*Carbohydrates	*Protein	*Total fat	*Dietary fibre total (g)	*Energy (KJ)	Ca** (mg)
Pearl millet	61.78 ± 0.85	10.96 ± 0.26	5.43 ± 0.64	11.49 ± 0.62	1456 ± 18	27.4
Sorghum	67.68 ± 1.03	09.97 ± 0.43	1.73±0.31	10.22± 0.49	1398 ± 13	27.6
Ragi	66.82 ± 0.73	07.16 ± 0.63	1.92 ± 0.14	11.18 ± 1.14	1342 ± 10	364.0
Little millet	65.55 ± 1.29	08.92 ± 1.09	2.55± 0.13	06.39 ± 0.60	1449 ± 19	16.1
Kodo millet	66.19 ± 1.19	08.92 ± 1.09	2.55 ± 0.13	06.39 ± 0.60	1388 ± 10	15.3
Foxtail millet	60.09	12.30	4.30	-	331	31.0
Barnyard millet	65.55	06.20	2.20	-	307	20.0
Proso millet	70.04	12.50	1.10	-	341	14.0

Millet	P** (mg)	Mg** (mg)	Zn** (mg)	Fe** (mg)	Thaimin (mg)	Riboflavin (mg)	Niacin (mg)	Folic acid (µg)
Pearl millet	289	124	2.7	6.4	0.25	0.20	0.9	36.1
Sorghum	274	133	1.9	3.9	0.35	0.14	2.1	39.4
Ragi	210	146	2.5	4.6	0.37	0.17	1.3	34.7
Little millet	130.0	91.0	1.8	1.2	0.26	0.05	1.3	36.2
Kodo millet	101.0	122.0	1.6	2.3	0.29	0.20	1.5	39.5
Foxtail millet	188.0	81.0	2.4	2.8	0.59	0.11	3.2	15.0
Barnyard millet	280.0	82.0	3.0	5.0	0.33	0.10	4.2	-
Proso millet	206.0	153.0	1.4	0.8	0.41	0.28	4.5	-

***per 100 g   **mg/g of N**

Source: Indian Food Composition Tables, NIN-2017 and Nutritive value of Indian Foods, NIN-2007

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MIXED METHODS MODELS IN SOCIAL SCIENCE RESEARCH

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Abstract
Mixed methods research (MMR) combines quantitative and qualitative approaches within a single inquiry to leverage their respective strengths and offset limitations. In social science, MMR provides a robust framework to examine complex and context-sensitive phenomena, enabling both breadth and depth of understanding. This article reviews philosophical foundations, major models—including convergent, sequential, embedded, transformative, and multistage designs—and strategies for integration, sampling, and analysis. It also highlights validity concerns, common pitfalls, and practical steps for planning. By emphasizing purposeful integration, MMR yields more comprehensive, credible, and contextually relevant insights than single-method approaches.

Keywords: Mixed methods research, social science, triangulation, integration, validity

Introduction

Mixed methods research (MMR) purposefully integrates quantitative and qualitative approaches within a single program of inquiry to capitalize on the strengths of each while offsetting their respective limitations (Johnson & Onwuegbuzie, 2004). In social science, where phenomena are complex, contextual, and value-laden, mixed methods models offer a principled way to ask multidimensional questions, connect "how many" with "how" and "why," and generate actionable, contextually grounded evidence (Creswell & Plano Clark, 2018; Greene *et al*., 1989). This article explains the philosophical foundations of MMR, overviews the most common mixed methods models (designs), details strategies for integrating data and inferences, summarizes sampling and analysis options, addresses quality/validity considerations, and closes with practical guidance for planning and reporting.

Philosophical and Paradigmatic Foundations

The most widely invoked philosophical rationale for MMR is pragmatism, the view that methodological choices should be driven by research purposes, questions, and consequences rather than by allegiance to any single paradigm (Morgan, 2007). Pragmatism rejects rigid quantitative–qualitative dichotomies and values multiple forms of warranted knowledge, making it especially suitable for problem-focused social research (Johnson & Onwuegbuzie, 2004; Tashakkori & Teddlie, 2010). Other justifications include dialectical pluralism, which deliberately engages tensions between paradigms to spur creative solutions, and transformative stances that center equity and voice in design decisions (Greene *et al*., 1989; Tashakkori & Teddlie, 2010).

Core Purposes for Mixing

Greene and colleagues (1989) identify five classic purposes that still guide model choice: triangulation (corroborating results across methods), complementarity (elaborating or clarifying results), development (informing one method with the results of the other), initiation (discovering paradoxes or contradictions), and expansion (extending breadth and scope). Being explicit about purpose helps align questions, timing, and integration points (Greene *et al*., 1989; Creswell & Plano Clark, 2018).

Mixed Methods Models (Designs)

Below are widely used, well-specified models. All require clarity about priority (which strand—qual or quant—has greater weight) and timing (concurrent vs. sequential) (Creswell & Plano Clark, 2018; Tashakkori & Teddlie, 2010).

1. Convergent (Concurrent Triangulation) Design

Quantitative and qualitative strands are conducted in parallel; findings are merged to compare, corroborate, or enrich interpretations at the end (Creswell & Plano Clark, 2018). This design is suitable when a comprehensive picture is needed within a single timeframe or when the researcher wishes to check consistency across methods (Bryman, 2006).

2. Explanatory Sequential Design (Quan → Qual)

This model begins with a quantitative phase to test relationships or estimate effects, followed by a purposeful selection of participants for qualitative interviews or observations to explain why the observed patterns occurred (Creswell & Plano Clark, 2018). It is commonly used in policy and program evaluation, where statistical effect sizes prompt mechanism-seeking qualitative inquiry (Venkatesh *et al*., 2013).

3. Exploratory Sequential Design (Qual → Quan)

The exploratory sequential design starts with qualitative inquiry to identify constructs, language, and processes, which then inform the development or adaptation of instruments tested quantitatively at scale (Creswell & Plano Clark, 2018). This approach is particularly useful when constructs are underdeveloped or context-specific (Schoonenboom & Johnson, 2017).

4. Embedded Design

In this model, one strand is nested within the other to answer a different but complementary question. For instance, a process-tracing qualitative component may be embedded in a randomized controlled trial, or a short survey might be incorporated within an ethnographic study (Creswell & Plano Clark, 2018).

5. Transformative and Participatory Designs

These designs are guided by a social justice lens, where participatory qualitative work helps co-define outcomes that are subsequently measured and analyzed through community-responsive approaches (Tashakkori & Teddlie, 2010).

6. Multistage/Complex Designs

Large-scale research programs may chain multiple phases, such as Qual → Quant → Qual, to iteratively build theory and test interventions. These complex designs require explicit integration across stages to produce coherent meta-inferences (Tashakkori & Teddlie, 2010; Creswell & Plano Clark, 2018).

Sampling in Mixed Methods

Mixed methods often combine probability (for generalizability) and purposeful (for depth/variation) sampling. Teddlie and Yu (2007) outline a typology: parallel sampling (both strands sampled independently), nested sampling (one sample draws from the other), and multilevel sampling (different levels for different strands). Purposeful strategies include maximum variation, extreme case, and theory-driven sampling, frequently used to explain quantitative heterogeneity or mechanisms (Teddlie & Yu, 2007; Creswell & Plano Clark, 2018).

Analytic Models and Data Transformation

Although mixed methods is broader than any single statistical technique, several modeling and transformation practices routinely scaffold integration:

- **Qual → Quant transformation**: Convert codes/themes into variables (e.g., presence/absence, intensity scores) for regression, SEM, or multilevel models. This supports tests of associations between emergent constructs and outcomes (Bazeley, 2009).
- **Quant → Qual selection**: Use statistical results (e.g., clusters, residuals, or propensity scores) to select information-rich cases for qualitative explanation (Venkatesh *et al.*, 2013).
- **Multilevel and longitudinal models**: Link micro-level qualitative mechanisms with macro-level quantitative trends; for instance, fit a two-level model while interpreting cross-level interactions with ethnographic evidence (Creswell & Plano Clark, 2018).

A simple integrated modeling move is to carry forward qualitative insights as theory-informed covariates or moderators in a quantitative model. For example, if interviews reveal a "service trust" mechanism M_i, you might operationalize it and test moderation:

$$Y_{ij} = \beta_0 + \beta_1 \text{Treatment}_{ij} + \beta_2 M_{ij} + \beta_3 (\text{Treatment}_{ij} \times M_{ij}) + u_j + \varepsilon_{ij},$$

where u_j is a group random effect capturing context and β_3 quantifies mechanism-by-treatment moderation suggested by the qualitative strand (Venkatesh *et al.*, 2013).

Validity, Quality, and Inference

MMR quality includes both within-strand standards (e.g., credibility/transferability in qualitative; reliability/validity in quantitative) and between-strand "legitimation" of integration (Onwuegbuzie & Johnson, 2006). Common threats and remedies include:

- **Sample integration legitimation**: Ensure qualitative participants adequately represent or meaningfully extend the quantitative frame; make selection logic explicit (Teddlie & Yu, 2007).
- **Inside–outside legitimation**: Balance emic (participant) and etic (researcher) perspectives; triangulate interpretations (Onwuegbuzie & Johnson, 2006).
- **Weakness minimization**: Use one method to address the other's limitations (e.g., qualitative depth to interpret statistically significant but small effects) (Johnson & Onwuegbuzie, 2004).
- **Sequential legitimation**: Guard against timing artifacts—e.g., when early qualitative categories unduly constrain later measurement, or when attrition between phases biases inference (Onwuegbuzie & Johnson, 2006).
- **Conversion legitimation**: When transforming data (qual→quant or quant→qual), document procedures and evaluate information loss (Bazeley, 2009).

Transparent reporting of integration points, priority, timing, and meta-inferences substantially improves credibility and reuse (Fetters *et al.*, 2013; Venkatesh *et al.*, 2013).

Practical Steps for Planning a Mixed Methods Study

1. **Start with purpose and questions.** State clearly what mixing will accomplish (e.g., explain heterogeneity; build a measure; corroborate findings) (Greene *et al.*, 1989).

2. **Choose a model that fits purpose and constraints.** Convergent for breadth/corroboration; explanatory sequential to interpret statistical results; exploratory sequential to develop measures (Creswell & Plano Clark, 2018).
3. **Plan integration early.** Specify how you will connect, build, and merge; sketch a joint display in your protocol (Fetters *et al*., 2013).
4. **Align sampling across strands.** Decide on parallel vs. nested designs and justify decisions relative to inference goals (Teddlie & Yu, 2007).
5. **Predefine analytic decisions.** For example, decide in advance how qualitative codes become variables and how contradictions between strands will be adjudicated (Bazeley, 2009).
6. **Attend to ethics and feasibility.** Mixing often increases burden; obtain consent for linked analysis across phases and protect confidentiality during integration (Creswell & Plano Clark, 2018).
7. **Report with clarity and parsimony.** Show the logic of mixing, the flow of timing and priority, and at least one joint display that links strands to meta-inferences (Fetters *et al*., 2013; Venkatesh *et al*., 2013).

Common Pitfalls and How to Avoid Them

- **Parallel play** without integration → *Solution*: Precommit to joint displays and integration questions (Fetters *et al*., 2013).
- **Underspecified sampling links** → *Solution*: Articulate how cases move across phases and why (Teddlie & Yu, 2007).
- **Overreliance on "triangulation"** as a catch-all → *Solution*: Use the precise purpose typology (triangulation, complementarity, development, initiation, expansion) to sharpen design logic (Greene *et al*., 1989).
- **Instrument drift from early qualitative work** → *Solution*: Pilot and cross-validate instruments in the quantitative phase; allow iterative refinement (Creswell & Plano Clark, 2018).
- **Unacknowledged contradictions** → *Solution*: Treat divergence as data; use initiation to refine theory or reveal subgroup processes (Greene *et al*., 1989; Bryman, 2006).

Conclusion

Mixed methods models provide a coherent, design-based pathway to integrate numerical generalization with contextual understanding in social science. Their value lies not in "using two methods," but in *purposeful* integration—connecting strands so that each informs, challenges, and strengthens the other, culminating in defensible meta-inferences. With clear purpose, an appropriate design, planned integration (merging/connecting/building), aligned sampling, and transparent reporting, mixed methods can yield findings that are both generalizable and meaningful on the ground (Creswell & Plano Clark, 2018; Johnson & Onwuegbuzie, 2004; Fetters *et al*., 2013).

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ADOPTION AND IMPACT OF MUD CRAB FATTENING PRACTICES ON THE WELL-BEING OF PAZHAVERKADU REGION FISHER-FOLKS

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Introduction

Pazhaverkadu, also known as Pulicat, is a coastal village nestled in the Thiruvallur district of Tamil Nadu, surrounded by mangrove ecosystems and brackish water lagoons. Traditionally reliant on capture fisheries, the community has faced seasonal income fluctuations, overfishing, and resource degradation. In response to these challenges, mud crab (*Scylla serrata*) fattening practices have emerged as a sustainable and profitable aquaculture option, significantly improving the socio-economic wellbeing of the local fishers and farmers. Mud crab fattening involves culturing juvenile or lean crabs until they reach a desirable size and weight for market. Crabs are typically stocked in pens, cages, or ponds and fed with fish scraps, mollusks, and formulated feeds for a short duration of 30–45 days (Gopalakrishnan et al., 2015). This low-investment, high-return model has proven especially attractive in coastal areas like Pazhaverkadu due to its compatibility with existing resources and skills.

Adoption in Pazhaverkadu

The widespread adoption of crab fattening in Pazhaverkadu was supported by agencies like:

Central Institute of Brackish water Aquaculture (CIBA), which provided training and technical know-how. 2)Tamil Nadu Fisheries Department, which facilitated access to seed and market linkages. 3) NGOs and Self-Help Groups (SHGs) that mobilized women and marginalized communities. Women in particular have shown increased participation, with many SHGs now independently managing crab fattening units (CIBA Annual Report, 2020). The Tamil Nadu Dr. J. Jayalalithaa Fisheries University (TNJFU) has been instrumental in promoting mud crab fattening in Pazhaverkadu. In 2018, TNJFU, in collaboration with the National Fisheries Development Board (NFDB), organized training programs to teach local fishers about site selection, pond preparation, feed management, and harvesting techniques .A significant milestone was the inauguration of mud crab hatchery units at the Pulicat Research Field Facility (PRFF) on January 29, 2025, by TNJFU's Vice Chancellor, Prof. N. Felix . This facility aims to provide quality crab seeds and technical support to local farmers.

Economic and Social Impact

1) Increased Income and Livelihood Security

Farmers reported a 200–300% increase in income compared to traditional fishing, with average returns of ₹25,000–₹40,000 per cycle from a small pond (Thirunavukkarasu & Kathirvel, 2020). According to a study conducted by the ICAR-Central Institute of Brackish water Aquaculture (ICAR-CIBA), mud crab fattening can yield a net income of ₹20,000–30,000 per cycle, with up to 8–10 cycles possible per year depending on the availability of seed and water quality (CIBA, 2022). This has helped many families achieve financial stability and invest in their children's education and household improvements.

2) Women Empowerment

Women SHGs now play a leading role, gaining financial independence and respect in their households and communities (Sathyanathan et al., 2018). A notable aspect of this initiative is the active involvement of local fisherwomen. In Kulathumedu village, women like Bujiyamma have successfully fattened crabs weighing up to 2 kg, selling them at approximately ₹1,200 per kg. This venture not only provides a steady income but also empowers women by enhancing their roles in community development. Another inspiring development is the active participation of women self-help groups (SHGs) in the crab fattening business. CIBA's "Sustainable Mud Crab Aquaculture Technology" has been successfully transferred to women's groups in Pazhaverkadu, enhancing their role in income generation and household decision-making (ICAR-CIBA Annual Report, 2022).

3) Reduced Migration and Youth Employment

Youth who previously migrated to urban areas now find local employment in pond construction, crab harvesting, and marketing. Under the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and state aquaculture missions:

- Youth have received free training on cage construction and feeding methods.
- Many have been supported with subsidized equipment and bank loans for startup.
- NGOs like M.S. Swaminathan Research Foundation (MSSRF) and self-help groups also play a key role in capacity building.
- The business is simple to manage, requires less than 4–6 hours of daily work, and provides quick income within 1 to 1.5 months per cycle.

4) Improved Quality of Life

Increased income has improved access to education, healthcare, and nutrition for many families. House repairs, asset purchases, and savings have also increased.Earlier, many young people from Pazhaverkadu migrated to urban areas like Chennai to work as daily-wage labours, hotel workers, or drivers. This migration often disrupted family life and exposed them to unsafe work conditions.

Now, mud crab fattening is providing

- Stable local employment
- Higher monthly income (₹20,000–30,000)
- Family cohesion and better quality of life

"Instead of struggling in the city, I now earn better by fattening crabs in my backyard pen," says Prakash, 26, who returned to Pazhaverkadu during the COVID-19 pandemic.

Environmental and Sustainability Benefits

Crab fattening does not require intensive feed or large-scale mechanization. Most farmers rely on locally available fish discards, making the practice cost-effective and environmentally friendly. Moreover, the brackish water lagoons and estuaries of Pazhaverkadu provide an ideal natural environment for crab rearing. Community-based models and training by NGOs and research organizations have ensured knowledge sharing and sustainable practices, promoting resilience among fishing communities Mud crab fattening is considered eco-friendly due to:

- Low input requirements.
- Minimal water exchange, thus avoiding effluent discharge.
- Utilization of local natural resources such as mangrove-associated estuaries.

Moreover, the presence of crab farming has indirectly promoted mangrove conservation, as mangroves offer ideal conditions for juvenile crab collection (Kathirvel & Rengasamy, 2019).

Challenges in Practices

Despite its benefits, some challenges persist:

- Limited availability of crab seed (juveniles).
- High mortality during transportation.
- Lack of direct market access, leading to exploitation by middlemen.
- Poor storage and cold chain infrastructure.

Additionally, climate variability and water quality changes pose threats to the survival rate and growth of crabs (Gopalakrishnan et al., 2017).

Recommendations and Future Prospects:

- Development of hatcheries for consistent seed supply.
- Establishment of cold chains and better transportation systems.
- Formation of cooperative marketing societies to reduce dependency on middlemen.
- Capacity building and training programs for improved farm management.

With continued support from institutions and the government, Pazhaverkadu can serve as a model village for sustainable crab aquaculture in India.

Conclusion

The adoption of mud crab fattening in Pazhaverkadu is a success story in community-based aquaculture. It has provided economic resilience, social empowerment, and environmental sustainability, transforming the lives of many small-scale fishers and women in the region. Continued investment in infrastructure, research, and capacity building can further amplify these gains and make crab farming a long-term pillar of rural development in coastal Tamil Nadu.

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