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# SEED PRIMING IN VEGETABLE CROPS: FROM INDIGENOUS KNOWLEDGE TO MODERN SEED TECHNOLOGY

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## Introduction

A successful vegetable crop begins with a seed that can germinate quickly, emerge uniformly and establish a vigorous seedling. Yet seeds often encounter difficult conditions immediately after sowing—low or high temperature, inadequate moisture, salinity, soil-borne pathogens and fluctuating environmental conditions. Seed priming offers a simple way of preparing seeds for these challenges before they enter the soil. *Seed priming is a controlled pre-sowing hydration treatment under controlled conditions in which seeds are allowed to imbibe sufficient water to initiate the early physiological processes of germination without permitting radicle emergence.* After treatment, the seeds are dried to a suitable moisture level and sown. Primed seeds can subsequently germinate faster and more uniformly than untreated seeds.

But the idea of preparing seed before sowing is not new. Farmers have traditionally soaked, coated or treated seeds with water, cow dung preparations, botanical materials, ash and other locally available substances. Modern seed science has now begun to explain some of the physiological and biological principles behind several of these practices. Thus, the story of seed priming is not simply about replacing traditional practices with modern technology; rather, it is also about understanding, validating and improving useful indigenous knowledge.

## Why does a seed need a head start?

Vegetable crops are particularly dependent on rapid and uniform establishment. Small-seeded crops such as carrot, onion, cabbage, cauliflower and lettuce may experience difficulty when the seedbed dries rapidly after sowing. In nursery-raised crops such as tomato, brinjal, chilli and many cucurbits, uneven emergence produces seedlings of different ages and sizes, complicating transplanting and subsequent crop management. Priming activates several processes inside the seed before sowing (Fig. 1). Research has demonstrated benefits of different priming methods in vegetable crops, including improvements in germination rate, germination speed and seedling vigour under suitable conditions.

## Traditional wisdom: Farmers were priming before the term existed

Long before laboratories began measuring germination kinetics, farmers developed methods to improve seed establishment using materials available around the farm. One of the simplest practices is water soaking. Seeds are soaked for a specified period and then dried or sown immediately. Although the duration varies with crop and local practice, the underlying principle resembles hydropriming, i.e., controlled hydration initiates metabolic activity before sowing. Farmers have also traditionally used cow dung slurry, cow urine-based preparations, ash and plant extracts for pre-

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sowing seed treatment. In natural farming (NF) systems, preparations such as *Beejamrit* are used for seed treatment and are promoted as a low-cost biological approach. ICAR has documented farmer training programmes involving the preparation and use of *Beejamrit* using cow dung and cow urine. Similarly, traditional botanical seed treatments have been documented in India. Materials derived from plants such as neem (*Azadirachta indica*), sweet flag (*Acorus calamus*), eucalyptus, mint and other botanicals have been used for protecting stored or planted seed. Several studies on indigenous seed treatment note their potential as alternatives to chemical seed treatments and highlight the need to scientifically validate useful indigenous knowledge.

These practices should not all be labelled simply as "seed priming". A water-soaking treatment is closer to hydropriming, whereas coating seeds with a botanical preparation or microbial formulation may be better classified as seed treatment or biopriming. The distinction is scientifically important.

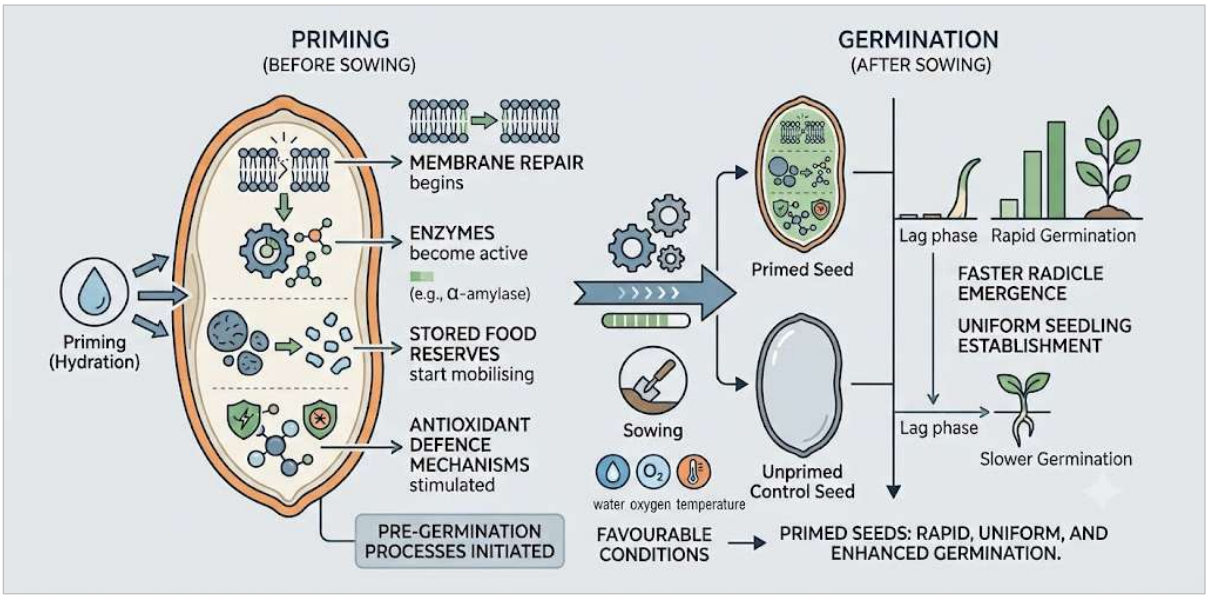



***Fig. 1. Physiological changes during seed priming***

**Traditional versus modern: What is actually different?**

The major difference lies in precision and understanding. Traditional farmers generally rely on locally available materials, experience, observation and crop-specific knowledge. The method may be inexpensive and easily accessible but can vary in concentration, treatment duration and preparation. In contrast, modern seed priming attempts to control these variables precisely. Researchers measure seed moisture content, water potential, temperature, duration of treatment, germination percentage, mean germination time and seedling vigour. In other words, traditional knowledge often asks "What worked for us in this field?", whereas modern seed science asks "Why did it work, under what conditions, and can the treatment be reproduced consistently?" The greatest opportunity lies in bringing these two approaches together.

**Different methods of seed priming**

**Hydropriming**

Hydropriming is perhaps the most straightforward modern priming method. Seeds are soaked in water for a controlled period and subsequently dried before sowing. Its major advantages are low cost, simplicity and the absence of specialised chemicals. It can be particularly attractive for small

and marginal farmers. However, soaking for too long can cause problems. If the seed crosses the threshold into radicle emergence, drying can damage the emerging embryo. Poorly aerated water can also create undesirable conditions. Therefore, the principle should not be "soak seeds as long as possible", but rather "hydrate seeds to the correct physiological stage".

**Osmopriming**

In osmopriming, seeds are placed in solutions with controlled water potential, commonly using materials such as polyethylene glycol or selected salts. This allows water uptake to be regulated more precisely than with simple water soaking. The seed can activate metabolic processes while radicle emergence is restricted. This makes osmopriming useful for experimental and commercial seed enhancement, although it requires greater technical control.

**Halopriming and nutrient priming**

In halopriming, seeds are treated with dilute salt solutions. In nutrient priming, selected nutrients are supplied during the treatment. These methods can potentially improve early nutrient availability and help seeds cope with certain environmental stresses. However, concentration is critical. A solution that stimulates one seed lot can inhibit another if the concentration is excessive. This is why recommendations should always be crop-, cultivar- and seed-lot-specific.

**Biopriming**

One of the most promising approaches for vegetable crops is biopriming, in which seeds are treated with beneficial microorganisms. Organisms such as selected strains of Trichoderma, Bacillus and Pseudomonas can colonise the seed surface or emerging rhizosphere and may promote seedling growth or suppress certain soil-borne pathogens. This approach is particularly relevant to vegetable production because diseases occurring during the seedling stage can rapidly reduce plant stand.

Traditional botanical treatments and modern biopriming share an interesting philosophy—using biological resources to protect and stimulate the seed rather than relying exclusively on synthetic chemicals. However, scientifically characterised microbial formulations provide much greater control over strain identity, dose and quality.

**Botanical priming**

Botanical seed treatment offers perhaps the clearest meeting point between indigenous knowledge and modern science. Farmers have traditionally used plant materials such as neem and other botanicals for protecting seed. Scientific research has identified antimicrobial, insecticidal and antioxidant compounds in several plant species, providing plausible biological explanations for some traditional practices. However, the effectiveness of botanical treatments depends on plant species, plant part, extraction method, concentration and treatment duration. ICAR research has specifically highlighted the need to validate indigenous botanical seed treatments scientifically rather than assuming that every traditional formulation will perform consistently. This is an important lesson: traditional knowledge should be tested, not dismissed, and neither should it be accepted uncritically.

**Beejamrit and farmer-led biological approaches**

In NF systems, Beejamrit is promoted as a seed treatment prepared using locally available biological materials. ICAR has documented farmer training on preparation and use of Beejamrit, illustrating its continuing relevance within farmer-oriented NF programmes. Field research has also investigated Beejamrit as a form of seed biopriming. For vegetable crops, however, crop-specific validation

remains important before recommending a particular formulation, concentration or treatment duration on a large scale.

**Nano-priming**

At the advanced end of the spectrum is nano-priming, in which appropriately formulated nanomaterials are used to influence germination and early plant development. Studies have investigated their potential to improve antioxidant defence, nutrient acquisition and tolerance to environmental stresses. However, nano-priming is still an emerging technology, and questions concerning concentration, nanoparticle characteristics, environmental behaviour and safety require careful consideration. Thus, nano-priming should currently be regarded as a promising research frontier rather than a universal recommendation for farmers.

**Which technique should a farmer choose?**

There is no single seed-priming technique that is best for every vegetable crop or every farming situation. The appropriate method depends on crop, seed quality, production environment, major constraint, available resources and the purpose of priming (Fig. 2). A farmer should therefore begin by identifying the problem rather than selecting a priming treatment simply because it is considered modern.

Perhaps the most important rule is often overlooked—priming cannot compensate for poor-quality seed. Before treating a large quantity of seed, farmers should consider its germination percentage, physical purity, seed age, moisture content and vigour. A small batch should first be treated and compared with untreated seed. If priming does not improve germination or emergence under the intended conditions, there is little reason to treat the entire seed lot. The treatment should also be followed by appropriate drying and storage practices. Some primed seeds may have reduced storage longevity, so seeds should preferably be primed close to the sowing period unless the particular commercial treatment is designed for storage.

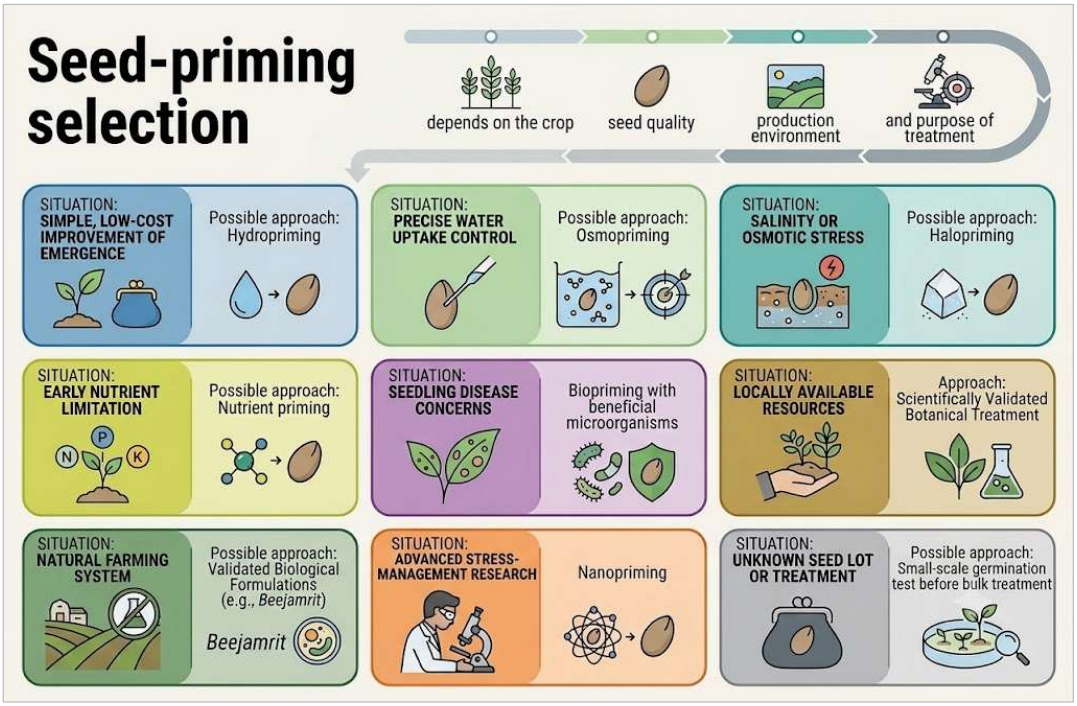



***Fig. 2. Choosing the appropriate seed priming technique according to crop production objectives***

Ultimately, the best seed priming technique is not necessarily the most sophisticated one. For a small farmer with good-quality seed and adequate soil moisture, simple hydropriming may be sufficient. In a saline field, a validated stress-oriented treatment may be more appropriate. In a disease-prone nursery, biopriming may offer greater value. In a high-tech protected cultivation system, precision or commercial priming may justify the additional cost.

The right priming technology is, therefore, the one that:

- ✓ solves the farmer's actual problem
- ✓ is appropriate for the crop and seed lot
- ✓ can be applied correctly
- ✓ provides a measurable benefit greater than its cost

**The future: Combining indigenous knowledge with seed science**

The future of seed priming may not lie exclusively in sophisticated laboratories. Some of the most useful technologies may emerge from combining indigenous knowledge with modern scientific validation. A farmer may know that soaking a particular seed in a locally prepared formulation improves establishment. A researcher can determine the optimum concentration, treatment duration, physiological mechanism and consistency of the response. The resulting technology can then be standardised without losing its low-cost and locally accessible character. Such an approach is especially valuable for smallholders who may not have access to expensive seed treatment equipment.

**Conclusion**

Seed priming represents a fascinating journey from traditional farmer wisdom to precision seed technology. Water soaking, botanical treatments and biological formulations reflect generations of practical experience, while hydropriming, osmopriming, biopriming, nutrient priming and nanopriming demonstrate how modern science is refining the same basic objective—helping the seed establish successfully. The goal should not be to decide whether traditional or modern techniques are inherently superior. Instead, the priority should be to identify which practice works, why it works, under what conditions it works, and how reliably it can be reproduced. For vegetable crops facing increasingly unpredictable temperatures, moisture stress, salinity and disease pressure, giving the seed a better start may become one of the simplest steps towards resilient production. The future of seed priming may, therefore, be neither purely traditional nor purely technological; it may be the science-backed refinement of farmers' own knowledge.

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# A TRADITIONAL OCTOPUS FISHING METHOD PRACTISED ALONG THE PALK BAY COAST OF RAMANATHAPURAM DISTRICT

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**Introduction**

Palk Bay is a shallow, semi-enclosed bay situated in southeast coast of India between Tamil Nadu (India) and Sri Lanka. In Tamil Nadu it spans five coastal revenue districts viz. Nagapattinam, Thiruvarur, Thanjavur, Pudukkottai, and Ramanathapuram. It stretches roughly 296 km from Point Calimere in Nagapattinam district to Dhanushkodi in Ramanathapuram district. Among them, Ramanathapuram district, which has a 261 kilometer coastline and borders both Palk Bay and the Gulf of Mannar, is the leading producer of marine finfish in Tamil Nadu due to its profitable fishing grounds and are most abundant in seaweeds, shellfish other economically significant species.

The traditional octopus fishing method is mainly practiced in Thondi ($9^0$ 43’26” N and $79^0$02’55”E) which is located in the Palk bay (Perumal et. al., 2021) along with its neighbouring villages such as Pasipattinam, Thirupalaikudi, Mullimonai, Allaiyankulam, Solliyakudi. The coastal water off this stretch is nutrient-rich and turbid, with a shallow depth of about 1-2 m, and owing to the low wave action prevailing in the region, the sea bottom sediment is predominantly muddy in nature. This shallow, nutrient-rich and low-energy environment supports a rich diversity of marine resources, including marine algae, coral reefs, seagrass beds, lobsters, molluscs and coelenterates (Perumal *et al*., 2021).

The primary source of income for the coastal inhabitants in this area is fishing, which is done using a variety of mechanized (trawling), motorized (gillnetting), and traditional (non-motorized) tools and equipment. However, a seasonal fishing ban is implemented on India's east coast from April 15 to June 15 each year, at which time trawling activities are prohibited in order to protect juvenile fish stocks and the ecologically delicate shallow-water ecosystem. Traditional, inexpensive, non-motorized gear such as the traditional octopus shell-trap known locally as Sangu Valai become especially important for the livelihood and financial security of the local fishing community during this ban period, when mechanized fishing is prohibited.

**Molluscan Fisheries – Cephalophods – Octopus - Behaviour and Biology**

Cephalopods, which include squids, cuttlefishes, and octopuses, are an economically significant and export-focused group of mollusks that are exploited along the Palk Bay coast. Due to rising export demand from the United States, Europe and Japan, India's cephalopod fisheries have grown significantly over the past ten years; in 2023, the country's estimated cephalopod landings reached about 2,12,517 tons, of which octopuses contributed 19,857 tons (9.3%). Octopuses are one of the least exploited cephalopod resources in India, despite being widely distributed along the coast. In

previous decades, octopuses were primarily caught as an incidental bait fishery rather than a targeted one. In Palk Bay, *Amphioctopus aegina* (Sandbird octopus / Aegina octopus) accounted for 77 % of all octopod catches (Rajkumar *et al*., 2024).

Octopuses belong to the Order Octopoda under Class Cephalopoda, and are placed under the Family Octopodidae. Octopuses have a highly developed brain and nervous system among invertebrates, enabling complex behaviors like learning, memory, and problem-solving. They excel in rapid camouflage through chromatophore control. Predominantly benthic, they inhabit crevices and shells on the sea floor, hiding during the day and foraging at night for crabs, bivalves, and small fishes. Their strong “denning” instinct seeking shelter in shells underpins the traditional gastropod shell-trap fishery (Ignatius *et al*., 2011).

**Sangu Valai a Trational Octopus Fisihg Trap**

The traditional method practised for octopus fishing along the Palk Bay coast of Ramanathapuram district is locally known as Sangu Valai (literally, “conch/shell net”), so named because empty gastropod shells are strung along a long line and set on the sea floor to catch octopus. This shell-trap or “pot-fishing” principle is a globally recognised, passive and non-destructive method of octopus fishing, in which hollow objects pots, shells or artificial dens are deployed to exploit the octopus's natural denning instinct, rather than actively pursuing, hooking or trawling the animal.

Sangu Valai has been practised for generations as an indigenous occupation along several traditional fishing villages of the Ramanathapuram coast of Palk Bay, including Thondi, Soliyakudi, Mullimunai and Thiruppalaikudi, passed down within fishing families through practical experience rather than formal training. The method assumes particular importance as a source of livelihood during the annual trawl-ban season, when it provides an eco-friendly, low-investment alternative source of income to the fishing community.

**Construction of Sangu Valai**

The gear is made using empty gastropod shells, collected as by-catch or sourced locally and cleaned. Commonly used shells include *Lambis lambis*, *Tonna dolium*, *Rapana bulbosa*, *Murex virgineus*, and *Murex hemitusus*. Each shell has a small hole drilled near the apex, through which a rope is knotted to attach it to the main line. Shells are spaced about 1 meter apart along a 5-6 km main line. Each line, made of 2 mm polypropylene rope, holds 3,000 to 3,500 shells, strong enough to bear their weight and the strain of hauling.To avoid tangling during setting and hauling operations, the completed long line, with shells strung along its entire length, is methodically coiled in baskets or trays on board the boat.



***Hauling of Sangu valai from the sea***



***Octopus from the shells of Sangu valai***

**Working Operation of Sangu Valai**

Three to four fishermen operate each of the small, non-motorized or outboard-motor-equipped FRP/wooden boats. Around 4:00 am, they set out, deploying a long line strung with shells along the chosen fishing area on the ocean floor. The line remains undisturbed for about a day. During this time, octopuses seeking cover from predators and light crawl into the empty shells, sometimes pulling a bivalve shell over the opening like an operculum for a false sense of security.

The next day, around 1:00 pm, fishermen return to the site, using a handheld GPS to locate the line and headlights for the floats. The boat moves slowly as the crew manually hauls the long line aboard, ensuring the line is lifted evenly to avoid snapping or entangling the shells. Each shell is checked, and any octopuses found are removed and placed directly into a seawater bucket on board to keep them alive until landing.The process becomes a continuous cycle instead of a single set-and-lift when all shells are checked, the long line is neatly rearranged to prevent tangling, and released back into the water at the same or a new location for the next day's retrieval.

**Income From Sangu Valai**

The Sangu Valai fishery has proved to be an economically viable and low-investment traditional gear for the fishing community. Since the gear involves only a one-time investment in gastropod shells and rope, and does not require fuel-intensive engine operation during the actual fishing process, the recurring operational cost is minimal compared to trawling or motorised gillnetting, making the returns from even a modest catch comparatively profitable for the fishermen involved.

Octopus commands a good market price compared to several other finfish landed along the Tamil Nadu coast, with average landing-centre prices reported in the range of about Rs. 150-220 per kg depending on size and season (NETFISH–MPEDA, Weekly Fish Price Reports). It is also increasingly sought after by exporters catering to international demand, particularly from the United States, Europe and Japan, where Indian frozen octopus has fetched export prices of roughly USD 2.5 to 8 per kg in recent years, depending on grade and market conditions. Owing to this steady demand and the low operational cost of the gear, Sangu Valai provides a comparatively low-cost, high-return livelihood option, particularly valuable during the annual trawl-ban period when other, more capital-intensive gears remain idle.

**Conclusion**

The traditional Sangu Valai fishery practised along the Palk Bay coast of Ramanathapuram district represents a unique, indigenous and ecologically sustainable method of exploiting the short-armed octopus, *Amphioctopus aegina*, based entirely on the animal's natural denning behaviour rather than on destructive or high-effort gear. Being a passive, low-cost and fuel-efficient method that does not damage the sea bed, corals or seagrass beds, it stands out as one of the most eco-friendly fishing practices of the region. Furthermore, with its low operational cost and steady market and export demand for octopus, the method provides a substantial and dependable source of income to the traditional fishing communities of Thondi, Soliyakudi, Mullimunai and Thiruppalaikudi, particularly during the trawl-ban season when alternative livelihood options are limited.

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# INTEGRATING AGRICULTURAL POLICIES AT THE VILLAGE LEVEL FOR SUSTAINABLE AND RESILIENT FARMING

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**Abstract**
Indian agriculture faces growing challenges from climate change, natural resource degradation, rising input costs, fragmented landholdings, and unstable markets, disproportionately affecting small and marginal farmers. Addressing these challenges requires effective integration of existing agricultural policies and programmes at the village level. This paper examines mechanisms for coordinating initiatives such as the National Mission for Sustainable Agriculture (NMSA), National Innovations in Climate Resilient Agriculture (NICRA), Soil Health Card Scheme, irrigation programmes, agricultural credit, crop insurance, and market support systems. It proposes a village-level convergence framework involving *agricultural departments, Krishi Vigyan Kendras, Panchayati Raj Institutions, Farmer Producer Organisations, financial institutions,* and *rural communities*. Key strategies include participatory planning, coordinated infrastructure development, strengthened extension services, accessible institutional credit, collective marketing, and outcome-based monitoring. Effective integration can improve resource-use efficiency, climate resilience, farm profitability, and equitable service delivery. The paper emphasizes farmer-centred institutional coordination as a pathway towards sustainable, inclusive, and economically viable agricultural development in India.

**Keywords:** Agricultural policy integration; Village-level planning; Sustainable agriculture; Climate resilience; Institutional convergence; Farmer Producer Organisations; Agricultural extension; Small and marginal farmers.

## Introduction

Indian agriculture faces increasing challenges from climate change, erratic rainfall, droughts, floods, declining soil health, groundwater depletion, rising input costs, fragmented landholdings, and volatile agricultural markets. These challenges disproportionately affect small and marginal farmers, tenant cultivators, women farmers, and resource-poor rural households. Addressing these vulnerabilities requires an integrated approach that combines productivity enhancement with resource conservation, livelihood security, and climate resilience.

India has introduced several important initiatives, including the National Mission for Sustainable Agriculture (NMSA), the National Innovations in Climate Resilient Agriculture (NICRA) programme, the Soil Health Card Scheme, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), and agricultural credit, insurance, and market-support programmes. However, fragmented implementation, limited interdepartmental coordination, uneven extension services, inadequate institutional convergence, and gaps in market access often restrict their collective impact at the village level.

The village provides a practical platform for integrating these initiatives through participatory planning, coordinated service delivery, and community-based resource management. Convergence

among *agricultural departments, Krishi Vigyan Kendras, Panchayati Raj Institutions, Farmer Producer Organisations (FPOs), banks,* and *local communities* can improve access to technology, credit, insurance, inputs, and remunerative markets. This paper examines mechanisms for strengthening village-level policy integration and institutional coordination to promote inclusive, resource-efficient, economically viable, and climate-resilient farming systems across India.

**The central challenge: from multiple schemes to one village development plan**

India has several agricultural programmes addressing climate resilience, soil health, irrigation, crop insurance, credit, extension and market development. However, vulnerable farmers often experience these services separately: soil testing may not lead to fertilizer recommendations; climate advisories may not reach farmers in time; credit may arrive after sowing; and increased production may not translate into better income because storage and marketing facilities are inadequate. The solution is to make the village, rather than the individual scheme, the unit of agricultural planning and service delivery. Each village should have one integrated agricultural development plan that brings together available government schemes, scientific institutions, panchayats, banks, FPOs and farmer groups. The goal is not necessarily to merge schemes administratively. It is to coordinate their planning, budgets where permissible, delivery schedules, beneficiary records and measurable outcomes.

**How major agricultural programmes can work together**

The following framework explains the complementary roles of key programmes and how to connect them in practice (Table 1).

**Table 1: Framework explaining complementary roles of key programmes and how to connect them in practice**

| Programme or institution | Primary contribution | Village-level integration mechanism |
|---|---|---|
| National Mission for Sustainable Agriculture (NMSA) | Sustainable farming, rainfed agriculture and natural-resource management | Prepare a resource-conservation plan linked to local soil, water and cropping constraints |
| National Innovations in Climate Resilient Agriculture (NICRA) | Climate-risk assessment, demonstrations and adaptation technologies | Use village climate-risk assessments to guide contingency plans, demonstrations and resilient crop choices |
| Soil Health Card (SHC) Scheme | Soil testing and nutrient-management recommendations | Connect test results to crop plans, fertilizer recommendations, input availability and follow-up field demonstrations |
| Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) | Irrigation efficiency and water-resource development | Link field irrigation, watershed treatment, farm ponds and drainage to a village water budget |
| National Food Security Mission (NFSM) | Productivity and technology adoption in selected crops | Align seed, nutrient, pest-management and demonstration support with local production opportunities |

| | | |
|---|---|---|
| Rashtriya Krishi Vikas Yojana (RKVY) | Support for state-led agricultural development initiatives | Finance eligible locally identified priorities through approved state plans and project mechanisms |
| Pradhan Mantri Fasal Bima Yojana (PMFBY) | Crop-risk insurance for eligible notified crops and areas | Improve enrolment awareness, crop-record accuracy, reporting of losses and claim follow-up |
| Agriculture Infrastructure Fund (AIF) | Financing for eligible post-harvest and community farming infrastructure | Help eligible FPOs and other entities prepare bankable storage, grading, processing and logistics projects |
| Formation and Promotion of 10,000 FPOs scheme | Farmer aggregation, collective services and market participation | Use FPOs to coordinate input procurement, machinery services, aggregation, quality control and marketing |
| Agricultural extension and KVK network | Research-based advice, demonstrations and farmer training | Provide a shared village extension calendar and joint demonstrations tied to seasonal decisions |

These programmes have distinct eligibility criteria, implementation channels and funding rules. The village plan should coordinate them without assuming that every village or farmer qualifies for every intervention.

**Establish a Village Agricultural Convergence Committee**

Every village or practical cluster of villages should have a Village Agricultural Convergence Committee (VACC), operating through the Gram Panchayat and coordinated with the block-level agriculture department. This is a proposed coordination mechanism, not a claim that a new committee is already mandated nationwide.

The committee should prepare one annual village plan, identify vulnerable households, sequence interventions and monitor outcomes. It should use existing panchayat and departmental structures wherever possible to avoid creating another layer of bureaucracy.

**Suggested membership and responsibilities**

**Gram Panchayat - local coordination:** Identify village priorities, convene meetings, coordinate community assets, maintain public action plans and review progress.

**Agriculture department, KVK and scientists - technical guidance:** Interpret soil results, prepare climate contingencies, organize demonstrations and provide crop-specific recommendations.

**FPOs, SHGs and farmer representatives - collective action:** Aggregate demand for inputs, arrange machinery services, organize produce collection and communicate farmers' priorities.

**Banks, PACS and other eligible financial institutions - financial access:** Identify credit gaps, support applications, plan seasonal credit and help viable collectives prepare finance proposals.

**Market committees, buyers and processors - market access:** Assess demand, quality requirements, storage needs, transport and opportunities for value addition.

**Women farmers, tenant cultivators, landless agricultural workers, small and marginal farmers, Scheduled Caste and Scheduled Tribe households, and other locally vulnerable groups:** Women farmers, tenant cultivators, landless agricultural workers, small and marginal farmers, Scheduled

Caste and Scheduled Tribe households, and other locally vulnerable groups should be represented. Participation should not depend exclusively on land ownership or membership in an FPO.

**The integrated village planning cycle**

The committee should follow a practical annual cycle linked to the agricultural seasons.

1. **Diagnose village risks:** Map soil fertility, groundwater, drainage, drought and flood exposure, crop patterns, livestock, farmer debt risks, existing infrastructure and market access.
2. **Prepare a single agricultural action plan:** Identify priority interventions, responsible agencies, eligible funding sources, implementation dates and expected benefits. Record which existing scheme can support each activity.
3. **Synchronize delivery:** Complete soil testing before fertilizer decisions, arrange seed and credit before sowing, deliver climate advisories during the season and prepare storage and marketing before harvest.
4. **Review and correct:** Hold seasonal reviews, resolve pending applications, check the quality of services, assess farmer feedback and revise the next season's plan.

**Use a shared village dashboard**

A simple spreadsheet or existing government MIS, with appropriate access controls, should record:

- Farmers requiring soil testing, credit, insurance or extension support.
- Soil-test results and whether recommendations were communicated and adopted.
- Crop-specific climate risks and contingency actions.
- Applications submitted, approved, pending or rejected, with reasons.
- FPO aggregation, storage capacity, buyer linkages and payment delays.
- Changes in production costs, net returns, crop losses and resource-use efficiency.

The committee should not create a parallel database containing unnecessary personal financial or identity information. Existing official records should be reused where lawful, and farmers should be able to correct errors and seek assistance offline.

A useful model already exists in the policy direction of the PM Dhan-Dhaanya Krishi Yojana, approved for 100 districts over six years beginning in 2025–26. Its design emphasizes convergence of existing schemes, crop diversification, irrigation, storage and credit. Village-level coordination can translate this approach into local action.

**5. Strengthening extension services: from advice to implementation**

Agricultural extension must go beyond distributing information. Farmers need timely, locally validated advice and support to implement it.

**Recommended mechanisms**

**A. Develop a village extension calendar:** KVKs and agriculture officers should jointly schedule advisories and demonstrations around actual decisions: seed selection, land preparation, sowing, fertilizer application, irrigation, pest surveillance and harvesting.

**B. Create farmer learning groups:** Establish crop-specific and farming-system groups that include women farmers, tenant cultivators and smallholders. Demonstration plots should compare locally relevant practices, recording yields, costs, labour requirements and profitability.

**C. Strengthen last-mile advisory delivery:** Combine WhatsApp or SMS messages, local-language voice messages, community radio where available, village meetings and field visits. Digital communication should supplement rather than replace personal extension.

**D. Build a cadre of trained local resource persons:** Train selected farmers, rural youth and women in soil sampling, nutrient recommendations, pest monitoring, weather advisories and safe input use. Provide supervision and refresher training through KVKs and the agriculture department.

**E. Introduce rapid climate-response protocols:** When forecasts indicate extreme rainfall, drought or heat, designated extension personnel should issue location-specific guidance on drainage, irrigation, fertilizer timing, crop protection and contingency options.

**F. Make extension accountable for results.** Measure farmer reach, timeliness, adoption, yield stability, net returns and satisfaction - not just the number of meetings or pamphlets distributed.

For example, the Soil Health Card system already supports soil testing and crop-specific nutrient recommendations. Its next step at village level should be to connect each result with an understandable nutrient plan, access to appropriate inputs and follow-up assessment. Official programme information also identifies village-level soil testing laboratories as an avenue for local service delivery.

**6. Making FPOs the operational link between farmers, schemes and markets**

FPOs can reduce transaction costs and improve bargaining power, but registration alone does not create a viable business. Many require professional management, working capital, dependable buyers and better infrastructure.

**Practical measures to strengthen FPOs**

1. **Build services around local production clusters:** Organize FPO activities around suitable crops, horticulture, dairy, pulses, oilseeds or other locally viable enterprises rather than creating identical business models everywhere.
2. **Provide professional business support:** Ensure access to trained chief executive officers, accountants, procurement managers, quality-assurance personnel and digital record-keeping.
3. **Develop a seasonal business plan:** Estimate member production, expected procurement volumes, quality standards, storage needs, transport costs, working capital and likely buyers before each crop season.
4. **Link FPOs with public programmes:** Help eligible FPOs access relevant support under the 10,000 FPO scheme, Agriculture Infrastructure Fund, Agricultural Marketing Infrastructure scheme and other applicable programmes, subject to their current guidelines and eligibility.
5. **Improve working-capital access:** Facilitate cash-flow-based lending, appropriate credit guarantees where available, transparent purchase agreements and faster buyer payments. Infrastructure subsidies alone cannot finance produce procurement.
6. **Encourage federations and shared services:** Smaller FPOs can pool transport, warehouses, processing, laboratory testing, marketing and professional services through federations or service providers.
7. **Protect member interests:** Maintain transparent accounts, disclose prices and charges, distribute benefits fairly and create accessible grievance mechanisms.

As reported by the Government in February 2026, the 10,000 FPO scheme provides eligible FPOs with management support, matching equity grants and access to credit-guarantee facilities, subject to scheme conditions. The Small Farmers' Agribusiness Consortium also recognizes the importance of federations in improving coordination and access to finance and markets.

**7. Improving credit accessibility for vulnerable farmers**

Credit should reach farmers when they need it, at a cost they can reasonably manage, and in a form appropriate to their production system.

**Proposed village-level credit mechanism**

1. **Conduct a pre-season credit assessment.** Identify requirements for seed, fertilizer, labour, irrigation, machinery hiring, livestock and post-harvest activities before the cropping season begins.
2. **Organize village credit camps:** Banks, PACS, eligible cooperative institutions and agricultural officers should help farmers complete applications, update records and understand loan terms.
3. **Improve access for tenant farmers and sharecroppers:** Work with eligible joint-liability groups, SHGs, farmer collectives and locally available institutional lending mechanisms so that lack of formal land title does not automatically exclude cultivators from consideration.
4. **Strengthen Kisan Credit Card access:** Help eligible farmers obtain, renew or correct their KCC records and understand applicable limits, interest terms, repayment schedules and concessions.
5. **Link credit with productive investment:** Combine appropriate seasonal credit with viable irrigation, machinery, livestock, storage or processing investments where repayment capacity is demonstrated.
6. **Coordinate credit with insurance and markets:** Explain insurance eligibility and claim procedures, and avoid repayment assumptions that depend on uncertain future prices or yields.

Banks should disclose the actual cost of borrowing, fees, repayment obligations and consequences of default in understandable language. Credit camps should not become a mechanism for pressuring farmers into unnecessary borrowing or unsuitable financial products.

A useful performance measure is the proportion of eligible farmers receiving the required credit before the relevant production activity, together with rejection reasons, processing times and subsequent repayment stress.

**8. Developing market and post-harvest infrastructure**

Production support is incomplete if farmers must sell immediately after harvest at low prices or cannot meet buyers' quality requirements. Coordinated infrastructure packages integrating irrigation, drainage, farm ponds, rural roads, storage facilities, cold chains, and digital connectivity can substantially improve agricultural productivity and resilience. Such integrated investments reduce post-harvest losses, improve market access, and lower production and transportation costs. Village-level planning ensures that infrastructure is complementary, locally appropriate, and accessible to small and marginal farmers. **Fig. 1** displays a Coordinated post-harvest infrastructure Packages.

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(A) Village collection and aggregation centres (B) Scientific storage and warehouse access



(C) Primary processing and value addition (D) Market connectivity and price transparency

***Fig. 1 A coordinated post-harvest infrastructure packages***

- **Establish weighing, grading, moisture testing, digital receipts and transparent payment systems:** FPOs or eligible cooperatives can operate facilities with panchayat coordination.
- **Develop suitable grain storage, warehouses and warehouse-receipt access.** For fruits and vegetables, prioritize appropriate packhouses, pre-cooling and cold chains only where volumes, energy supply and buyer demand justify their costs.
- **Primary processing and value addition:** Support cleaning, grading, milling, oil extraction, sorting, packaging and other appropriate activities through shared facilities and commercially viable FPO enterprises.

Connect producers to mandis, institutional buyers, processors, retailers and appropriate digital platforms. Compare net prices after transport, grading, storage and commission costs. The Agriculture Infrastructure Fund, Agricultural Marketing Infrastructure scheme and e-NAM can support different parts of this system, depending on project eligibility and state implementation arrangements. Infrastructure investments should follow a local market assessment. A warehouse without sufficient throughput, a cold store without reliable electricity or buyers, or a processing

plant without working capital can become a financial liability rather than a source of farmer income. Fig. 1 displays Integrated Agricultural Policies at the Village Level for Sustainable and Resilient Farming.

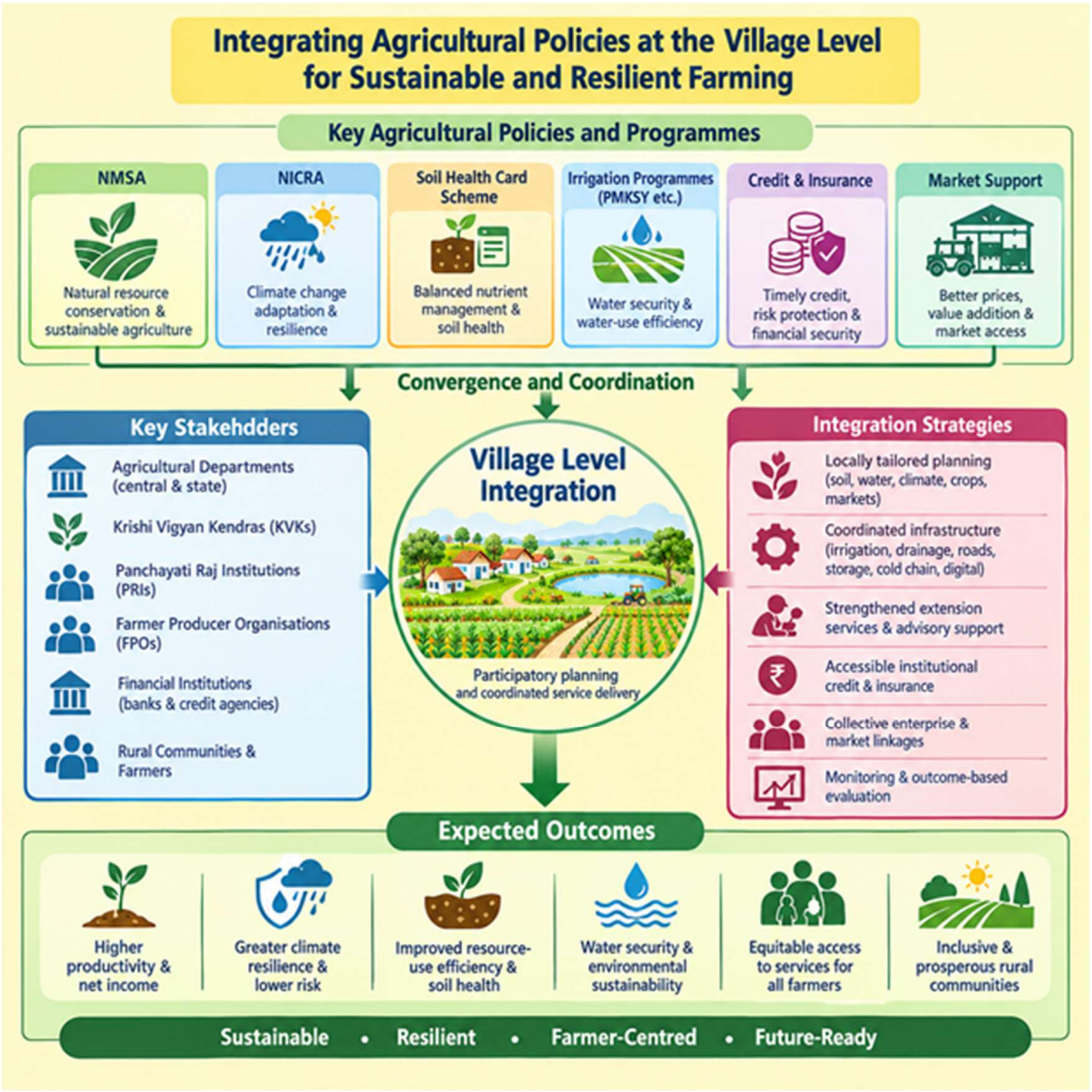



Fig. 1 Integrated agricultural policies at the village level for sustainable and resilient farming

**9. An illustrative village convergence plan**

The following example shows how coordinated implementation could work in a hypothetical 1,000-household village with small farms, seasonal water stress, imbalanced fertilizer use and weak market access (**Table 2**)

**Table 2 Coordinated implementation**

| Identified problem | Coordinated intervention | Lead and supporting institutions | Measurable result |
|---|---|---|---|
| Soil fertility uncertainty | Soil sampling, fertility mapping and demonstrations of | Agriculture department, soil laboratory, KVK | More farmers following suitable soil-test recommendations |

| Identified problem | Coordinated intervention | Lead and supporting institutions | Measurable result |
|---|---|---|---|
| | balanced nutrient management | | |
| Drought and excessive rainfall | Water budgeting, drainage maintenance, farm ponds and contingency crop planning | Panchayat, irrigation and agriculture departments, farmer groups | Lower avoidable crop losses and improved water management |
| High input costs | FPO input procurement, machinery hiring and farm-cost records | FPO, PACS where available, extension personnel | Lower avoidable costs and better net returns |
| Weak institutional credit access | Pre-season credit camps and application tracking | Banks, PACS and eligible lending institutions | Higher timely credit access among eligible farmers |
| Distress sales | Aggregation, grading, storage and multiple buyer linkages | FPO, market agencies, processors and buyers | Reduced post-harvest losses and improved net sale realization |
| Limited technical support | Seasonal demonstrations, local-language advisories and field visits | KVK, agriculture officers and trained local resource persons | Timely adoption of suitable practices |
| Fragmented schemes | Annual convergence plan and shared progress review | Gram Panchayat and block-level coordination team | Fewer service gaps, unresolved applications and duplicated activities |

The village should establish a baseline before implementation and set realistic numerical targets based on local conditions, available funds and staffing.

**10. Implementation roadmap**

Select a phase to see the main actions and deliverables.
First 3 months: organize and diagnose
Months 4–6: deliver priority services
Months 7–12: connect finance and markets
Year 2 onward: evaluate and scale

Organize and diagnose

- Constitute or designate the village coordination mechanism using existing institutions where possible.
- Map vulnerable households, crops, soil and water constraints, credit gaps and infrastructure.
- Review available schemes, eligibility, budgets and pending applications.
- Approve a public, season-specific action plan.

Deliverable: Village agricultural vulnerability map and approved action plan.

**11. Monitoring: measure outcomes rather than expenditure alone**

The block and district administrations should review a concise set of indicators every season (**Table 3**)

**Table 3 Monitoring measure outcomes**

| Dimension | Suggested indicators |
|---|---|
| Extension | Farmers reached, advice delivered on time, adoption and farmer satisfaction |
| Soil health | Samples tested, recommendations communicated, nutrient balance and soil organic carbon trends |
| Climate resilience | Crop losses, recovery time and use of contingency plans |
| Credit | Timely disbursement, application rejection reasons and repayment stress |
| FPO performance | Member participation, business revenue, payment timeliness and repeat buyers |
| Markets | Post-harvest losses, storage utilization and net farm-gate prices |
| Inclusion | Access to services among smallholders, women farmers, tenant cultivators and other vulnerable groups |
| Sustainability | Net farm income, water productivity, input efficiency and yield stability |

An independent or participatory annual review should validate these indicators. An increase in the number of cards issued, meetings held, loans sanctioned or facilities built is not sufficient evidence of improved farmer welfare unless services are accessible and deliver meaningful outcomes.

**Conclusion**

India can improve agricultural sustainability by connecting existing programmes through a unified village-level planning and accountability framework in which NMSA guides natural resource conservation, NICRA supports climate adaptation, Soil Health Cards inform balanced nutrient management, extension services facilitate the adoption of appropriate technologies, Farmer Producer Organisations (FPOs) promote collective enterprise, financial institutions ensure timely credit, and market infrastructure enables farmers to capture greater value from their produce. Effective implementation requires locally tailored interventions based on village-specific soil, water, climate, cropping systems, and market conditions, supported by strong institutional coordination, clearly defined responsibilities, shared seasonal schedules, and mechanisms to address gaps between departments. Progress should be measured not merely by programme expenditure or the number of beneficiaries but by tangible improvements in farmers' net income, reduced production risks, healthier natural resources, and equitable access to essential services. Ultimately, the objective is to establish an integrated, farmer-centred support system that enables vulnerable farmers to access appropriate advice, quality inputs, affordable finance, effective risk protection, and remunerative market opportunities at the right time, without having to navigate fragmented institutional arrangements independently.

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# AGRIVOLTAICS: A DUAL LAND-USE APPROACH FOR SUSTAINABLE AGRICULTURE AND SOLAR ENERGY GENERATION

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## Introduction

Agriculture and renewable energy are essential for sustainable development, food security and rural economic growth. Increasing electricity demand, climate change and growing pressure on agricultural land have created a need for technologies that utilize natural resources more efficiently. Solar photovoltaic (PV) energy is an important clean energy option because it generates electricity directly from sunlight. However, conventional ground-mounted solar power plants may occupy land that could otherwise support agricultural production. This concern has encouraged the development of integrated approaches that combine farming activities with renewable energy generation. Agrivoltaics, also known as agrophotovoltaics, is an emerging dual land-use approach in which agricultural crops and solar PV systems share the same land. Solar modules are installed at suitable heights and spacing to allow crop cultivation beneath or between the panels. The concept of combining solar energy conversion with agricultural production was introduced by Goetzberger and Zastrow (1982). Later, Dupraz *et al*., (2011) demonstrated through modelling that integrating photovoltaic panels with crop production could improve overall land-use efficiency compared with separating the two activities.

Beyond electricity generation, agrivoltaic systems may influence the growing environment of crops by modifying sunlight availability, soil temperature and moisture conditions. Partial shading can benefit certain crops under hot and dry conditions, although excessive shading may reduce productivity. Therefore, the effectiveness of agrivoltaics depends on appropriate crop selection, solar panel arrangement and local environmental conditions. In India, where agricultural livelihoods and solar energy development are both important, agrivoltaics offers opportunities for more efficient land utilization, decentralized electricity generation and diversified farm income. With suitable technical design and agricultural management, this approach could contribute to sustainable farming practices while supporting the expansion of renewable energy infrastructure.

## Understanding Agrivoltaic Technology and Its Working Principle

Agrivoltaic technology is based on the coordinated use of sunlight for both electricity generation and agricultural production. In this system, solar photovoltaic (PV) modules are positioned above or between cultivated areas using specially designed mounting structures. The arrangement of these modules allows agricultural operations to continue while utilizing part of the available solar radiation for electricity generation. Unlike conventional solar installations, agrivoltaic systems require careful consideration of crop requirements, farming activities and energy production during

system design. The working principle involves the conversion of sunlight into electrical energy through the photovoltaic effect. When solar radiation strikes PV cells, electrical energy is generated and supplied through the associated electrical system. Meanwhile, sunlight reaching the ground directly through spaces between modules, together with diffuse radiation, supports crop photosynthesis. The distribution of light across the cultivated area depends on panel height, tilt angle, orientation, row spacing and seasonal changes in the position of the sun.

Solar panels can also modify the microclimate surrounding agricultural crops. Under suitable conditions, partial shading may reduce excessive solar exposure, moderate crop temperatures and limit water loss from the soil. These changes can benefit certain crops in hot and water-limited environments. However, crops differ in their sunlight requirements, and excessive shading can reduce photosynthetic activity and yield. Therefore, effective agrivoltaic design requires a suitable balance between electricity generation and agricultural productivity (Marrou *et al*., 2013; Barron-Gafford *et al*., 2019; Weselek *et al*., 2019).

**Types of Agrivoltaic Systems**

Agrivoltaic systems can be classified according to the arrangement, mounting height and orientation of solar photovoltaic (PV) modules. The selection of a suitable configuration depends on crop characteristics, agricultural operations, available land and local solar radiation conditions. The three commonly used configurations are described below.

1. **Elevated Agrivoltaic Systems:** In this configuration, solar PV modules are mounted on raised supporting structures, allowing crops to grow beneath the panels. The elevated arrangement provides space for irrigation, field operations and, where sufficient clearance is available, agricultural machinery. Panel height and spacing are selected to maintain adequate sunlight for crop growth. Although elevated structures may require higher initial investment, they can support continued agricultural use of the land.
2. **Vertical Bifacial Agrivoltaic Systems:** These systems consist of vertically installed bifacial solar panels, generally arranged in parallel rows. Bifacial modules can generate electricity using sunlight received on both their front and rear surfaces. Crops are cultivated between the rows, where panel spacing is designed to provide access for farming activities and limit excessive shading. East–west-facing module surfaces are one possible arrangement, depending on site conditions and electricity generation objectives.
3. **Adjustable or Tracking Agrivoltaic Systems:** Adjustable agrivoltaic systems use PV modules whose tilt angle or orientation can be changed manually or through automated tracking mechanisms. This arrangement provides opportunities to manage the distribution of sunlight between panels and crops at different times. However, tracking structures involve additional mechanical components, maintenance requirements and investment costs.

Each configuration offers different advantages and limitations. Therefore, agrivoltaic system selection should consider agricultural productivity, electricity generation, installation costs and long-term operational requirements rather than focusing on solar power output alone.

**Benefits of Agrivoltaics for Agriculture and Farmers**

Agrivoltaic technology offers opportunities to improve agricultural sustainability by combining crop production with renewable electricity generation. Its major advantage is the productive utilization of the same land for two purposes, potentially reducing competition between agricultural activities

and solar energy development. However, the benefits depend on system design, crop selection and local environmental conditions.

**Improved Land-Use Efficiency:** Agrivoltaic systems enable farmers to continue cultivating crops while producing electricity from solar panels installed on the same land. This combined use can improve overall land productivity compared with maintaining separate areas for farming and solar power generation.

**Crop Protection and Water Conservation:** Partial shading from solar panels may protect selected crops from excessive solar radiation and high temperatures. Under hot and dry conditions, shading can also reduce soil evaporation and improve moisture availability. However, excessive shading may negatively affect crops that require high sunlight intensity.

**Additional Income Opportunities:** Agrivoltaics may provide farmers with opportunities to diversify their income through electricity generation, leasing arrangements or partnerships with solar energy developers. The actual financial benefits depend on installation costs, electricity tariffs, maintenance expenses and contractual arrangements.

**Renewable Energy for Agricultural Operations:** Electricity generated through agrivoltaic installations can potentially support irrigation pumps, agricultural equipment, cold storage and other farm operations, subject to appropriate electrical connections and energy management systems.

**Environmental Sustainability:** By integrating renewable energy generation with agricultural activities, agrivoltaics can support more efficient land utilization and reduce dependence on fossil fuel-based electricity. Well-designed systems may also contribute to improved resilience against heat and water stress in suitable agricultural environments.

**Agrivoltaics In India: Opportunities and Applications**

India offers considerable potential for agrivoltaic development due to its abundant solar resources, extensive agricultural land and increasing demand for renewable energy. Integrating solar photovoltaic systems with farming can improve land-use efficiency, support decentralized electricity generation and create additional income opportunities for farmers. However, successful adoption requires technologies suited to diverse agro-climatic conditions and cropping patterns (Mohammad *et al*., 2024).

Agrivoltaic demonstration projects in India, including installations in Gujarat, have explored the integration of solar electricity generation with crop cultivation. These initiatives provide opportunities to evaluate crop performance, shading effects and agricultural operations under different solar panel arrangements (Medonna & Ghosh, 2025).

Agrivoltaics may benefit selected vegetables, medicinal plants and fodder crops that tolerate partial shading, particularly in hot and water-limited regions. However, crop suitability requires location-specific field evaluation (Ghamari *et al*., 2026). Wider adoption will depend on affordable financing, farmer awareness, technical support and suitable government policies.

**Challenges and Future Prospects of Agrivoltaics**

Despite its potential, agrivoltaic technology faces technical, economic and operational challenges. High installation costs, specialized mounting structures, limited technical expertise and difficulties in accommodating agricultural machinery may restrict adoption. Excessive shading can also reduce

the productivity of sunlight-demanding crops, making appropriate system design and crop selection essential.

Another major challenge is the lack of standardized recommendations for different crops and agro-climatic regions. Financial constraints, maintenance requirements and limited access to suitable electricity marketing arrangements may further discourage small and marginal farmers (Chopdar *et al*., 2024).

Future advancements in bifacial solar modules, adjustable mounting structures, intelligent tracking systems and crop-specific shading management could improve agrivoltaic performance. Greater emphasis on field research, affordable technologies, farmer training and supportive policies will be essential for wider implementation. Collaboration between agricultural institutions and renewable energy developers can help establish practical and economically viable agrivoltaic systems in India (Asa'a *et al*., 2024).

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# AREA, PRODUCTION AND PRODUCTIVITY OF FRUIT CROPS IN HIMACHAL PRADESH

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## Introduction

Fruit growing is a major source of income for farm families in Himachal Pradesh. The state grows a wide range of fruits, from apples, pears, plums and stone fruits in the higher hills of Shimla, Kullu, Kinnaur and Mandi to mango, litchi, guava and citrus in the lower hills of Kangra, Una, Bilaspur and Hamirpur. This variety makes the district picture very uneven, both in how much land is under fruit and in how much each hectare yields. This article uses the Department of Horticulture's district-wise data for 2024-25 and 2025-26 to compare the area, production and productivity (production per hectare) of 37 fruit crops across 12 districts. It ranks crops and districts by their share in each measure, names the leading crop and district, and compares the two years and their average to show what changed and which crops and districts are driving the state totals.

## State-level picture

| Indicator | 2024-25 | 2025-26 | 2-yr average | Change |
|---|---|---|---|---|
| Area (ha) | 2,37,368 | 2,33,733 | 2,35,551 | −1.5% |
| Production (MT) | 6,48,325 | 8,41,873 | 7,45,099 | +29.9% |
| Productivity (MT/ha) | 2.73 | 3.60 | 3.17 | +31.9% |

The area under fruits shrank slightly (by 3,635 ha), yet production rose by about 1.94 lakh MT. The whole gain came from apple. Apple production rose by 1,96,928 MT (5,02,948 to 6,99,876 MT), which is more than the total state increase of 1,93,548 MT. All other fruits together fell from

1,45,377 MT to 1,41,997 MT (−2.3%). The state's fruit economy therefore moves very closely with the apple crop.

**Crop-wise share of area (maximum to minimum)**

Crops are ranked by the two-year average of 2024-25 and 2025-26; the average and its share are in the last two columns. Area in hectares.

| Rank | Crop | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 1 | Apple | 1,16,338 | 49.01 | 1,14,877 | 49.15 | 1,15,608 | 49.08 |
| 2 | Mango | 42,503 | 17.91 | 42,165 | 18.04 | 42,334 | 17.97 |
| 3 | B./K. Lime | 12,652 | 5.33 | 12,507 | 5.35 | 12,580 | 5.34 |
| 4 | Plum | 9,089 | 3.83 | 8,867 | 3.79 | 8,978 | 3.81 |
| 5 | Orange/Kinnow | 8,832 | 3.72 | 8,815 | 3.77 | 8,824 | 3.75 |
| 6 | Litchi | 6,955 | 2.93 | 6,790 | 2.91 | 6,873 | 2.92 |
| 7 | Pear | 6,278 | 2.64 | 5,895 | 2.52 | 6,087 | 2.58 |
| 8 | Peach | 4,753 | 2.00 | 4,614 | 1.97 | 4,684 | 1.99 |
| 9 | Almond | 4,071 | 1.72 | 3,872 | 1.66 | 3,972 | 1.69 |
| 10 | Walnut | 4,133 | 1.74 | 3,560 | 1.52 | 3,847 | 1.63 |
| 11 | Guava | 3,226 | 1.36 | 3,344 | 1.43 | 3,285 | 1.39 |
| 12 | Apricot | 3,117 | 1.31 | 2,820 | 1.21 | 2,969 | 1.26 |
| 13 | Malta/Mausammi | 2,536 | 1.07 | 2,711 | 1.16 | 2,624 | 1.11 |
| 14 | Galgal | 2,566 | 1.08 | 2,454 | 1.05 | 2,510 | 1.07 |
| 15 | Aonla | 2,475 | 1.04 | 2,429 | 1.04 | 2,452 | 1.04 |
| 16 | Pomegranate | 2,362 | 1.00 | 2,233 | 0.96 | 2,298 | 0.98 |
| 17 | Jackfruit | 2,017 | 0.85 | 2,059 | 0.88 | 2,038 | 0.87 |
| 18 | Persimmon | 1,110 | 0.47 | 1,488 | 0.64 | 1,299 | 0.55 |
| 19 | Pecan nut | 794 | 0.33 | 635 | 0.27 | 715 | 0.30 |
| 20 | Cherry | 347 | 0.15 | 339 | 0.15 | 343 | 0.15 |
| 21 | Kiwi | 257 | 0.11 | 306 | 0.13 | 282 | 0.12 |
| 22 | Jamun | 268 | 0.11 | 279 | 0.12 | 274 | 0.12 |
| 23 | Papaya | 211 | 0.09 | 191 | 0.08 | 201 | 0.09 |
| 24 | Grape Fruit | 66 | 0.03 | 65 | 0.03 | 66 | 0.03 |
| 25 | Banana | 63 | 0.03 | 61 | 0.03 | 62 | 0.03 |
| 26 | Grapes | 60 | 0.03 | 56 | 0.02 | 58 | 0.02 |
| 27 | Deon | 54 | 0.02 | 54 | 0.02 | 54 | 0.02 |
| 28 | Loquat | 53 | 0.02 | 52 | 0.02 | 53 | 0.02 |
| 29 | Spota | 49 | 0.02 | 47 | 0.02 | 48 | 0.02 |
| 30 | Strawberry | 34 | 0.01 | 34 | 0.01 | 34 | 0.01 |
| 31 | Karonda | 19 | 0.01 | 19 | 0.01 | 19 | 0.01 |
| 32 | Beal | 18 | 0.01 | 20 | 0.01 | 19 | 0.01 |
| 33 | Other Fruit | 16 | 0.01 | 22 | 0.01 | 19 | 0.01 |
| 34 | Ber | 18 | 0.01 | 18 | 0.01 | 18 | 0.01 |
| 35 | Olive | 13 | 0.01 | 8 | 0.00 | 11 | 0.00 |

| Rank | Crop | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 36 | Hazelnut | 7 | 0.00 | 14 | 0.01 | 11 | 0.00 |
| 37 | Fig | 8 | 0.00 | 13 | 0.01 | 11 | 0.00 |
| | **State total** | 2,37,368 | 100 | 2,33,733 | 100 | 2,35,551 | 100 |

**Highest area: Apple** (49.0% in 2024-25; 49.2% in 2025-26), followed by Mango (about 18%) and Baramasi/Kagzi Lime (about 5.3%). Apple and mango together hold roughly two-thirds of the fruit area. **Lowest area:** Olive (8 ha), Fig (13 ha) and Hazelnut (14 ha) in 2025-26.

**Crop-wise share of production (maximum to minimum)**

Production in metric tonnes, ranked by the two-year average.

| Rank | Crop | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 1 | Apple | 5,02,948 | 77.58 | 6,99,876 | 83.13 | 6,01,412 | 80.72 |
| 2 | Mango | 44,933 | 6.93 | 45,017 | 5.35 | 44,975 | 6.04 |
| 3 | Pear | 16,584 | 2.56 | 16,505 | 1.96 | 16,545 | 2.22 |
| 4 | Plum | 14,974 | 2.31 | 14,320 | 1.70 | 14,647 | 1.97 |
| 5 | Orange/Kinnow | 14,644 | 2.26 | 14,037 | 1.67 | 14,341 | 1.92 |
| 6 | B./K. Lime | 9,289 | 1.43 | 8,593 | 1.02 | 8,941 | 1.20 |
| 7 | Litchi | 7,639 | 1.18 | 6,849 | 0.81 | 7,244 | 0.97 |
| 8 | Guava | 6,990 | 1.08 | 6,316 | 0.75 | 6,653 | 0.89 |
| 9 | Apricot | 4,355 | 0.67 | 4,379 | 0.52 | 4,367 | 0.59 |
| 10 | Galgal | 4,286 | 0.66 | 4,122 | 0.49 | 4,204 | 0.56 |
| 11 | Peach | 3,348 | 0.52 | 4,588 | 0.54 | 3,968 | 0.53 |
| 12 | Pomegranate | 2,903 | 0.45 | 2,643 | 0.31 | 2,773 | 0.37 |
| 13 | Malta/Mausammi | 2,564 | 0.40 | 2,874 | 0.34 | 2,719 | 0.36 |
| 14 | Aonla | 2,070 | 0.32 | 1,850 | 0.22 | 1,960 | 0.26 |
| 15 | Persimmon | 1,784 | 0.28 | 1,852 | 0.22 | 1,818 | 0.24 |
| 16 | Walnut | 1,880 | 0.29 | 1,419 | 0.17 | 1,650 | 0.22 |
| 17 | Cherry | 1,777 | 0.27 | 1,335 | 0.16 | 1,556 | 0.21 |
| 18 | Papaya | 1,454 | 0.22 | 1,037 | 0.12 | 1,246 | 0.17 |
| 19 | Almond | 1,084 | 0.17 | 1,227 | 0.15 | 1,156 | 0.16 |
| 20 | Jackfruit | 1,007 | 0.16 | 1,015 | 0.12 | 1,011 | 0.14 |
| 21 | Kiwi | 965 | 0.15 | 936 | 0.11 | 951 | 0.13 |
| 22 | Jamun | 175 | 0.03 | 289 | 0.03 | 232 | 0.03 |
| 23 | Grape Fruit | 167 | 0.03 | 168 | 0.02 | 168 | 0.02 |
| 24 | Banana | 131 | 0.02 | 190 | 0.02 | 161 | 0.02 |
| 25 | Pecan nut | 145 | 0.02 | 145 | 0.02 | 145 | 0.02 |
| 26 | Grapes | 95 | 0.01 | 98 | 0.01 | 97 | 0.01 |
| 27 | Deon | 37 | 0.01 | 45 | 0.01 | 41 | 0.01 |
| 28 | Strawberry | 23 | 0.00 | 36 | 0.00 | 30 | 0.00 |
| 29 | Loquat | 23 | 0.00 | 29 | 0.00 | 26 | 0.00 |

| Rank | Crop | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 30 | Spota | 12 | 0.00 | 40 | 0.00 | 26 | 0.00 |
| 31 | Karonda | 12 | 0.00 | 14 | 0.00 | 13 | 0.00 |
| 32 | Beal | 6 | 0.00 | 12 | 0.00 | 9 | 0.00 |
| 33 | Other Fruit | 6 | 0.00 | 6 | 0.00 | 6 | 0.00 |
| 34 | Olive | 7 | 0.00 | 3 | 0.00 | 5 | 0.00 |
| 35 | Hazelnut | 5 | 0.00 | 5 | 0.00 | 5 | 0.00 |
| 36 | Ber | 2 | 0.00 | 2 | 0.00 | 2 | 0.00 |
| 37 | Fig | 1 | 0.00 | 1 | 0.00 | 1 | 0.00 |
| | **State total** | 6,48,325 | 100 | 8,41,873 | 100 | 7,45,099 | 100 |

**Highest production: Apple**, at 77.6% of the state's fruit output in 2024-25 and 83.1% in 2025-26. Mango is a distant second (6.9% and 5.4%). Note that mango's share fell only because apple grew; its tonnage was almost unchanged (44,933 to 45,017 MT). Apple, mango, pear, plum and Orange/Kinnow together contribute about 92% (2024-25) and 94% (2025-26) of production. **Lowest production:** Fig (1 MT), Ber (2 MT) and Olive (3 MT) in 2025-26.

The comparison with area is revealing. Apple holds about 49% of the area but 78-83% of the production. Mango holds 18% of the area but only 5-7% of the production. Citrus fruits as a group (Lime, Kinnow, Malta, Galgal, Grape Fruit) occupy about 11% of the area (26,652 ha and 26,552 ha) and produced 30,950 MT and 29,794 MT.

**Crop-wise productivity (maximum to minimum)**

Productivity in MT/ha. Ranked by the simple average of the two yearly productivity figures; the last two columns give the rank in each year.

| Rank (avg) | Crop | 2024-25 | 2025-26 | 2-yr average | Rank 24-25 | Rank 25-26 |
|---|---|---|---|---|---|---|
| 1 | Papaya | 6.89 | 5.43 | 6.16 | 1 | 2 |
| 2 | Apple | 4.32 | 6.09 | 5.21 | 3 | 1 |
| 3 | Cherry | 5.12 | 3.94 | 4.53 | 2 | 3 |
| 4 | Kiwi | 3.75 | 3.06 | 3.41 | 4 | 5 |
| 5 | Pear | 2.64 | 2.80 | 2.72 | 5 | 6 |
| 6 | Banana | 2.08 | 3.11 | 2.60 | 8 | 4 |
| 7 | Grape Fruit | 2.53 | 2.58 | 2.56 | 6 | 7 |
| 8 | Guava | 2.17 | 1.89 | 2.03 | 7 | 8 |
| 9 | Galgal | 1.67 | 1.68 | 1.68 | 9 | 10 |
| 10 | Grapes | 1.58 | 1.75 | 1.67 | 13 | 9 |
| 11 | Plum | 1.65 | 1.61 | 1.63 | 11 | 11 |
| 12 | Orange/Kinnow | 1.66 | 1.59 | 1.63 | 10 | 12 |
| 13 | Apricot | 1.40 | 1.55 | 1.48 | 14 | 13 |
| 14 | Persimmon | 1.61 | 1.24 | 1.43 | 12 | 14 |
| 15 | Pomegranate | 1.23 | 1.18 | 1.21 | 15 | 15 |
| 16 | Mango | 1.06 | 1.07 | 1.06 | 17 | 16 |
| 17 | Litchi | 1.10 | 1.01 | 1.05 | 16 | 20 |

| Rank (avg) | Crop | 2024-25 | 2025-26 | 2-yr average | Rank 24-25 | Rank 25-26 |
|---|---|---|---|---|---|---|
| 18 | Malta/Mausammi | 1.01 | 1.06 | 1.04 | 18 | 17 |
| 19 | Strawberry | 0.68 | 1.06 | 0.87 | 24 | 18 |
| 20 | Peach | 0.70 | 0.99 | 0.85 | 22 | 21 |
| 21 | Jamun | 0.65 | 1.04 | 0.84 | 25 | 19 |
| 22 | Aonla | 0.84 | 0.76 | 0.80 | 19 | 24 |
| 23 | Deon | 0.69 | 0.83 | 0.76 | 23 | 23 |
| 24 | B./K. Lime | 0.73 | 0.69 | 0.71 | 20 | 26 |
| 25 | Karonda | 0.63 | 0.74 | 0.68 | 26 | 25 |
| 26 | Spota | 0.24 | 0.85 | 0.55 | 34 | 22 |
| 27 | Hazelnut | 0.71 | 0.36 | 0.54 | 21 | 32 |
| 28 | Jackfruit | 0.50 | 0.49 | 0.50 | 28 | 29 |
| 29 | Loquat | 0.43 | 0.56 | 0.50 | 30 | 28 |
| 30 | Beal | 0.33 | 0.60 | 0.47 | 32 | 27 |
| 31 | Olive | 0.54 | 0.38 | 0.46 | 27 | 31 |
| 32 | Walnut | 0.45 | 0.40 | 0.43 | 29 | 30 |
| 33 | Other Fruit | 0.38 | 0.27 | 0.32 | 31 | 34 |
| 34 | Almond | 0.27 | 0.32 | 0.29 | 33 | 33 |
| 35 | Pecan nut | 0.18 | 0.23 | 0.21 | 35 | 35 |
| 36 | Ber | 0.11 | 0.11 | 0.11 | 37 | 36 |
| 37 | Fig | 0.12 | 0.08 | 0.10 | 36 | 37 |
| | **State average** | 2.73 | 3.60 | 3.17 | | |

**Highest productivity:** In 2024-25 the highest productivity was recorded by Papaya (6.89 MT/ha), followed by Cherry (5.12) and Apple (4.32). In 2025-26 Apple took the top place at 6.09 MT/ha, ahead of Papaya (5.43) and Cherry (3.94). Papaya and cherry are very small crops (211 ha and 347 ha in 2024-25), so apple is the only large crop among the top performers. **Lowest productivity:** Fig (0.12 and 0.08 MT/ha), Ber (0.11) and Pecan nut (0.18 and 0.23). Many nut and minor fruits (almond, walnut, pecan nut, hazelnut) stay below 0.5 MT/ha, which may reflect young or non-bearing plantations and dry-weight reporting; this should be checked with the department before drawing conclusions.

**Notable changes in productivity:** Apple +41% (4.32 to 6.09), Banana +50%, Strawberry +56%, Peach +41% and Spota nearly 3.5 times (from a very low base). Declines were seen in Cherry (−23%), Papaya (−21%), Hazelnut (−49%), Persimmon (−23%) and Kiwi (−18%). Mango, the second-largest crop, was flat at about 1.06-1.07 MT/ha.

**District-wise comparison**

**Area**

| Rank | District | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 1 | Shimla | 48,843 | 20.58 | 48,730 | 20.85 | 48,787 | 20.71 |
| 2 | Kangra | 41,789 | 17.61 | 41,823 | 17.89 | 41,806 | 17.75 |
| 3 | Mandi | 39,084 | 16.47 | 39,178 | 16.76 | 39,131 | 16.61 |

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| Rank | District | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 4 | Kullu | 31,436 | 13.24 | 31,480 | 13.47 | 31,458 | 13.36 |
| 5 | Sirmaur | 15,809 | 6.66 | 15,863 | 6.79 | 15,836 | 6.72 |
| 6 | Chamba | 17,307 | 7.29 | 13,556 | 5.80 | 15,432 | 6.55 |
| 7 | Kinnaur | 12,656 | 5.33 | 12,658 | 5.42 | 12,657 | 5.37 |
| 8 | Bilaspur | 8,450 | 3.56 | 8,523 | 3.65 | 8,487 | 3.60 |
| 9 | Hamirpur | 8,108 | 3.42 | 8,155 | 3.49 | 8,132 | 3.45 |
| 10 | Una | 6,270 | 2.64 | 6,327 | 2.71 | 6,299 | 2.67 |
| 11 | Solan | 5,684 | 2.39 | 5,516 | 2.36 | 5,600 | 2.38 |
| 12 | Lahaul-Spiti | 1,932 | 0.81 | 1,924 | 0.82 | 1,928 | 0.82 |
| | State total | 2,37,368 | 100 | 2,33,733 | 100 | 2,35,551 | 100 |

Shimla, Kangra, Mandi and Kullu together hold about 68% of the fruit area. Area is almost unchanged in every district except Chamba, which lost 3,751 ha (−21.7%), mainly under apple (12,728 to 11,470 ha), walnut (1,331 to 837 ha), apricot (360 to 112 ha), plum (341 to 95 ha) and lime (506 to 287 ha).

**Production**

| Rank | District | 2024-25 | Share % | 2025-26 | Share % | 2-yr average | Avg share % |
|---|---|---|---|---|---|---|---|
| 1 | Shimla | 2,95,235 | 45.54 | 4,55,117 | 54.06 | 3,75,176 | 50.35 |
| 2 | Kullu | 97,860 | 15.09 | 1,39,973 | 16.63 | 1,18,917 | 15.96 |
| 3 | Kinnaur | 97,438 | 15.03 | 69,843 | 8.30 | 83,641 | 11.23 |
| 4 | Mandi | 47,512 | 7.33 | 65,662 | 7.80 | 56,587 | 7.59 |
| 5 | Kangra | 52,582 | 8.11 | 52,655 | 6.25 | 52,619 | 7.06 |
| 6 | Sirmaur | 21,206 | 3.27 | 17,622 | 2.09 | 19,414 | 2.61 |
| 7 | Una | 14,905 | 2.30 | 15,572 | 1.85 | 15,239 | 2.05 |
| 8 | Bilaspur | 6,598 | 1.02 | 6,947 | 0.83 | 6,773 | 0.91 |
| 9 | Chamba | 5,487 | 0.85 | 7,916 | 0.94 | 6,702 | 0.90 |
| 10 | Solan | 6,185 | 0.95 | 6,565 | 0.78 | 6,375 | 0.86 |
| 11 | Hamirpur | 2,069 | 0.32 | 2,464 | 0.29 | 2,267 | 0.30 |
| 12 | Lahaul-Spiti | 1,248 | 0.19 | 1,537 | 0.18 | 1,393 | 0.19 |
| | **State total** | 6,48,325 | 100 | 8,41,873 | 100 | 7,45,099 | 100 |

Production is far more concentrated than area. Shimla (about 21% of area) produced 45.5% of the state's fruit in 2024-25 and 54.1% in 2025-26. Shimla, Kullu and Kinnaur together accounted for 75.7% and 79.0% of production. Production grew sharply in Shimla (+54.2%), Kullu (+43.0%), Chamba (+44.3%) and Mandi (+38.2%), but fell in **Kinnaur (−28.3%)** and Sirmaur (−16.9%). Kangra was practically unchanged (+0.1%).

**Productivity**

| Rank (avg) | District | 2024-25 | 2025-26 | 2-yr average | Rank 24-25 | Rank 25-26 |
|---|---|---|---|---|---|---|
| 1 | Shimla | 6.04 | 9.34 | 7.69 | 2 | 1 |

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| Rank (avg) | District | 2024-25 | 2025-26 | 2-yr average | Rank 24-25 | Rank 25-26 |
|---|---|---|---|---|---|---|
| 2 | Kinnaur | 7.70 | 5.52 | 6.61 | 1 | 2 |
| 3 | Kullu | 3.11 | 4.45 | 3.78 | 3 | 3 |
| 4 | Una | 2.38 | 2.46 | 2.42 | 4 | 4 |
| 5 | Mandi | 1.22 | 1.68 | 1.45 | 7 | 5 |
| 6 | Kangra | 1.26 | 1.26 | 1.26 | 6 | 6 |
| 7 | Sirmaur | 1.34 | 1.11 | 1.23 | 5 | 8 |
| 8 | Solan | 1.09 | 1.19 | 1.14 | 8 | 7 |
| 9 | Bilaspur | 0.78 | 0.82 | 0.80 | 9 | 9 |
| 10 | Lahaul-Spiti | 0.65 | 0.80 | 0.72 | 10 | 10 |
| 11 | Chamba | 0.32 | 0.58 | 0.45 | 11 | 11 |
| 12 | Hamirpur | 0.26 | 0.30 | 0.28 | 12 | 12 |
| | **State average** | 2.73 | 3.60 | 3.17 | | |

State average productivity was 2.73 MT/ha in 2024-25 and 3.60 MT/ha in 2025-26. Only three districts, Shimla, Kinnaur and Kullu, are above the state average in both years; they are the apple districts. Una (2.4-2.5 MT/ha) comes next, helped by mango and citrus, but stays below the state average. The big-area districts of Kangra and Mandi, which are mainly mango, citrus and litchi districts, have productivity of only 1.2-1.7 MT/ha. Chamba and Hamirpur are at the bottom, below 0.6 MT/ha.

**Why the apple belt explains the district picture**
**Apple productivity by district (MT/ha):**

| District | Apple area 2024-25 (ha) | Apple prod. 2024-25 (MT) | Yield 2024-25 | Apple area 2025-26 (ha) | Apple prod. 2025-26 (MT) | Yield 2025-26 | Avg yield |
|---|---|---|---|---|---|---|---|
| Shimla | 42,468 | 2,81,246 | 6.62 | 42,451 | 4,40,684 | 10.38 | 8.50 |
| Kullu | 27,435 | 79,917 | 2.91 | 27,439 | 1,22,997 | 4.48 | 3.70 |
| Mandi | 17,132 | 35,653 | 2.08 | 16,976 | 53,660 | 3.16 | 2.62 |
| Chamba | 12,728 | 4,200 | 0.33 | 11,470 | 6,886 | 0.60 | 0.47 |
| Kinnaur | 10,937 | 96,636 | 8.84 | 10,963 | 68,983 | 6.29 | 7.56 |
| **Himachal (all districts)** | 1,16,338 | 5,02,948 | 4.32 | 1,14,877 | 6,99,876 | 6.09 | 5.21 |

Shimla alone has 36-37% of the apple area and produced 55.9% (2024-25) and 63.0% (2025-26) of the apple crop. Its apple yield of 10.38 MT/ha in 2025-26 is the highest in the state. Kinnaur, with only about 9.5% of the apple area, gave 19.2% of the apple crop in 2024-25 at 8.84 MT/ha, but dropped to 6.29 MT/ha and 9.9% of the crop in 2025-26. This single movement explains Kinnaur's fall in overall production and productivity. Kullu, Mandi and Chamba improved markedly. Apple area is almost unchanged in all districts, so the rise in output is a yield story, not an area story.

**Main findings**

1. **Apple dominates on every measure:** highest area (about 49%), highest production (77.6% rising to 83.1%) and, in 2025-26, highest productivity (6.09 MT/ha).

2. **State production rose about 30% on 1.5% less area.** Productivity went from 2.73 to 3.60 MT/ha, driven wholly by apple.
3. **Non-apple fruits stagnated or declined** (−2.3% in production). Mango, citrus, litchi, guava, plum, pear, walnut and apricot all produced less or about the same.
4. **Mango is second in area (18%) but has low productivity (about 1.07 MT/ha),** pointing to scope for improvement in the lower-hill districts.
5. **Shimla leads in production and productivity, Kinnaur is the most volatile.** Kinnaur had the highest productivity in 2024-25 (7.70) and Shimla in 2025-26 (9.34).
6. **Kangra, Mandi, Chamba and Hamirpur have large areas but low productivity,** so they hold the main potential for gains through better varieties, rejuvenation of old orchards and irrigation.
7. **Chamba's area fell 21.7%,** the only significant change in area. The reasons need to be verified at the district level.

***Source:*** *Department of Horticulture, Himachal Pradesh, district-wise area and production of fruits, 2024-25 and 2025-26. Productivity, shares and percentage changes calculated by the author.*

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# NEW PRECISION AGRONOMY: A SMART PATHWAY TOWARDS PRODUCTIVE AND ENVIRONMENTALLY SUSTAINABLE AGRICULTURE

**Aakash Ojha[1*], Sandeep Manuja[1], Ashish Kumar[1], Pankaj Chopra[1], Shivali Rana[1], Kanika Baghla[2] , Shivanshu Ladohia[1] and Rijula[1]**

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## Introduction

Agriculture is essential for global food security, rural livelihoods and economic development. However, modern agricultural systems are increasingly challenged by rising food demand, soil degradation, water scarcity, climate change, environmental pollution and increasing input costs. Conventional farming practices have contributed significantly to food production, but uniform application of fertilizers, pesticides and irrigation water may not always meet the actual requirements of crops across an entire field. Variations in soil fertility, moisture availability, topography, crop growth and pest pressure can result in the overuse of inputs in some areas and insufficient application in others (Goswami *et al*., 2023). These inefficiencies may increase production costs, reduce resource-use efficiency and negatively affect soil and water quality. Therefore, there is a growing need for agricultural approaches that can increase productivity while conserving natural resources and protecting the environment.

**New precision agronomy** represents an integrated approach that combines scientific agronomic principles with digital technologies to manage crops according to their specific needs and field conditions. Unlike conventional farming, which often relies on general recommendations, precision agronomy uses information from soil testing, crop sensors, satellite imagery, drones, weather stations, geographical information systems (GIS) and global navigation satellite systems (GNSS) to identify variability within agricultural fields. Artificial intelligence (AI), machine learning, the Internet of Things (IoT) and decision-support systems can further transform this information into practical recommendations for nutrient management, irrigation, crop protection and harvesting (MacPherson *et al*., 2022). The approach is also evolving from observing existing crop conditions towards predictive agronomy, in which historical and real-time data help anticipate crop requirements and potential stress before serious damage occurs (Ceccarelli *et al*., 2022).

The primary objective of new precision agronomy is to achieve productive, profitable and environmentally sustainable agriculture by applying the right input at the right place, in the right amount and at the right time. It can support efficient fertilizer use, improve irrigation scheduling, facilitate targeted pest and weed management, reduce unnecessary field operations and strengthen climate resilience (Goswami *et al*., 2023). Nevertheless, technology alone cannot guarantee sustainability; its success depends on reliable data, local validation, farmer training, affordability and integration with good agronomic practices. In countries such as India, where small and fragmented landholdings are common, precision technologies must be adapted to local farming conditions and made accessible through affordable equipment, shared services and effective extension support

(Shamshiri *et al*., 2024). Thus, new precision agronomy provides an opportunity to connect agricultural innovation with long-term environmental stewardship and food security.

**Evolution from conventional to precision agronomy**

Conventional agronomy generally relies on standard fertilizer recommendations, fixed irrigation schedules and visual field observations. Although these practices remain useful, they may not fully account for differences in soil properties and crop requirements within a field. Precision agronomy addresses this limitation by dividing fields into management zones and adjusting inputs according to measured conditions (MacPherson *et al*., 2022). Predictive agronomy extends this concept by using crop models, weather forecasts, sensor observations and AI-based analysis to estimate future crop needs and identify potential risks.

This transition can help farmers move from reactive management towards timely, data-supported decisions. For example, instead of applying nitrogen uniformly across a wheat field, crop sensors and soil information can help identify areas requiring different fertilizer rates. Similarly, soil-moisture sensors and weather data can support irrigation decisions based on actual water requirements rather than a fixed calendar. The effectiveness of these methods depends on appropriate calibration and validation under local conditions.

**Major technologies used in new precision agronomy**

**1. GNSS, GPS and GIS**

Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), provide location information for agricultural machinery and field operations. GPS-guided tractors and implements can improve the accuracy of sowing, fertilizer placement, spraying and harvesting while reducing overlap and missed areas. GIS stores and analyses spatial information to generate maps of soil fertility, crop health, moisture availability and yield variability (Pradipta *et al*., 2022). Together, these technologies help farmers identify management zones and implement site-specific crop management.

**2. Satellite remote sensing and drones**

Satellite remote sensing enables repeated monitoring of crop growth over large areas. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge (NDRE) can help assess crop vigour and identify areas showing possible nutrient deficiency, water stress or disease-related damage. Drones equipped with multispectral or thermal cameras provide high-resolution images that help detect variations within individual fields. These observations can guide targeted field inspection, soil sampling, irrigation planning and fertilizer application. However, remote sensing generally identifies crop stress rather than definitively establishing its cause; field observations and diagnostic testing are often required for confirmation (Alexopoulos *et al*., 2023).

**3. Soil and crop sensors**

Proximal sensors measure soil or crop characteristics directly in the field. Soil sensors can monitor moisture, temperature and electrical conductivity, while optical crop sensors assess canopy reflectance and crop vigour. Tools such as GreenSeeker use reflected red and near-infrared light to calculate vegetation indices and support nitrogen-management decisions in suitable cropping systems. When combined with GPS and variable-rate application equipment, sensor measurements can help farmers adjust fertilizer rates according to crop conditions. Reliable recommendations require suitable calibration, soil testing and consideration of crop growth stage (Huck *et al*., 2024).

**4. Internet of Things, artificial intelligence and machine learning**

IoT systems connect sensors, weather stations, irrigation equipment and digital platforms to facilitate the collection and transmission of agricultural data. Soil-moisture readings, temperature, humidity and weather forecasts can be combined to support timely irrigation and crop monitoring. AI and machine-learning algorithms can analyse large datasets from satellites, drones, soil sensors and farm machinery to estimate crop yields, identify patterns of crop stress and forecast potential production risks (Pradipta *et al*., 2022). These tools can support early warnings and decision-making, but their accuracy depends on representative training data and validation across different crops, soils and climatic conditions.

**5. Big data, yield mapping and decision-support systems**

Yield monitors fitted to harvesting machinery can record crop yield and location, generating maps that reveal high- and low-productivity areas. Comparing yield maps from multiple seasons with soil fertility, topography, weather and management records can help explain field variability. Decision-support systems combine such information with crop models and agronomic recommendations to assist farmers in selecting fertilizer doses, irrigation schedules, sowing dates and crop-protection measures (Huck *et al*., 2024). Digital platforms can also integrate field records, input costs and crop performance, making farm management more systematic and traceable.

**6. Variable-rate technology and site-specific nutrient management**

Variable-rate technology (VRT) allows agricultural machinery to change the application rate of fertilizers, seeds or other inputs while moving through a field. Prescription maps prepared from soil tests, crop sensors and yield information can guide the application of different quantities in different management zones. Site-specific nutrient management (SSNM) similarly aims to match fertilizer application to crop demand and the soil's nutrient-supplying capacity. These approaches can improve nutrient-use efficiency and reduce unnecessary fertilizer application when recommendations are properly developed and implemented. Their benefits vary with soil conditions, crop response, equipment accuracy and the quality of the underlying data (Pradipta *et al*., 2022).

**7. Agricultural robotics and precision crop protection**

Agricultural robots and smart machinery are increasingly being developed for precision seeding, mechanical weeding, crop monitoring, targeted spraying and harvesting. Computer-vision systems can identify weeds or selected crop targets, enabling treatment of specific areas rather than entire fields. Precision pest and disease management can combine remote sensing, field scouting, weather information and integrated pest management (IPM) to identify infestation hotspots and guide timely interventions. Targeted treatment may reduce unnecessary pesticide use, although it must be supported by accurate detection, appropriate application technology and established pest-management recommendations (Getahun *et al*., 2024).

**Contribution to environmental sustainability and productivity**

The major strength of precision agronomy is its potential to improve resource-use efficiency while maintaining or increasing crop productivity. Site-specific fertilizer management can reduce excessive application and help minimise nutrient losses through leaching, runoff and gaseous emissions. Precision irrigation can improve water productivity by matching water application to crop requirements, soil moisture and weather conditions. Targeted weed and pest management may reduce unnecessary chemical use and associated environmental risks (Huck *et al*., 2024). More

accurate field operations can also reduce overlapping machinery passes, fuel consumption and avoidable labour costs.

Precision agronomy can contribute to soil conservation by identifying areas vulnerable to erosion, compaction or declining fertility. Repeated monitoring of soil and crop conditions can support improved management over successive seasons. Under variable climatic conditions, weather-based decision-support systems may help farmers plan irrigation, sowing and other field operations more effectively. However, these benefits should be demonstrated through measurements of yield, profitability, fertilizer and water use, greenhouse gas emissions, soil health and ecological impacts. Digitalisation can itself require energy, equipment and infrastructure, so its overall environmental performance should be evaluated rather than assumed (Getahun *et al*., 2024).

**Application and relevance in Indian agriculture**

India has diverse cropping systems, soil types and climatic conditions, making field-specific crop management particularly relevant. Precision agronomy can support crops such as rice, wheat, maize, cotton, sugarcane, fruits and vegetables through improved nutrient management, irrigation scheduling and crop-health monitoring. For example, in rice–wheat systems, soil testing and crop-based nutrient recommendations can help improve fertilizer-use efficiency (Ceccarelli *et al*., 2022). In maize, remote sensing and crop sensors may help identify uneven crop growth and potential moisture or nutrient stress. In horticultural crops, drip irrigation combined with soil-moisture sensors can support more precise water delivery.

Despite its potential, adoption remains challenging for many small and marginal farmers. High initial costs, fragmented landholdings, limited connectivity, inadequate technical training and a lack of locally calibrated datasets can restrict the practical use of advanced equipment. Shared machinery through custom hiring centres, affordable sensor systems, mobile-based advisory services, farmer training and collaboration with agricultural universities may improve accessibility. Public research institutions and extension agencies also have an important role in evaluating technologies under local conditions and communicating reliable recommendations. Digital agriculture initiatives should be designed around farmers' needs, languages, resources and decision-making practices rather than technology availability alone (Goswami *et al*., 2023).

**Challenges and future prospects**

The future of precision agronomy will depend on combining technological advances with sound agronomic science. Important priorities include developing affordable tools for small farms, improving rural connectivity, generating reliable local datasets and validating AI models across crops, seasons and regions. Interoperability between machinery, sensors and digital platforms is also needed so that farmers can use data without being restricted to incompatible systems (MacPherson *et al*., 2022). Data privacy, ownership, equipment maintenance and long-term economic viability require careful consideration.

Emerging technologies such as agricultural digital twins, autonomous machinery, edge AI and advanced decision-support systems may provide further opportunities for real-time crop monitoring and predictive management. Nevertheless, new technologies should be assessed through field trials that measure not only crop yield but also profitability, resource savings, greenhouse gas emissions, soil quality and biodiversity. Combining precision tools with crop rotation, integrated nutrient management, conservation agriculture and IPM can help ensure that technological improvements contribute to broader sustainability goals (Shamshiri *et al*., 2024).

**Conclusion**

New precision agronomy represents an important step towards more efficient, productive and environmentally responsible agriculture. By integrating GNSS/GPS, GIS, remote sensing, drones, soil and crop sensors, IoT, AI, yield mapping and variable-rate technology, it enables management decisions to be tailored to the actual needs of crops and the variability of agricultural fields. These practices can improve nutrient and water-use efficiency, reduce unnecessary input expenditure and support timely crop protection. However, their success depends on reliable data, local validation, affordability, farmer participation and effective extension services. For India, the priority is to develop accessible, scalable and locally appropriate precision solutions that benefit farmers with different landholding sizes. Ultimately, the goal is not merely to digitise farming, but to produce more efficiently while conserving soil, water, energy and biodiversity for future generations.

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# CLIMATE-SMART SOIL AND WATER MANAGEMENT: INTEGRATING AI, IOT AND GIS FOR SUSTAINABLE AGRICULTURAL RESOURCE CONSERVATION

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**Abstract**
Sustainable soil and water management is essential for agricultural productivity, resource conservation and climate resilience. Groundwater depletion, soil erosion, increasing irrigation demand and irregular rainfall pose significant challenges to Indian agriculture. Artificial Intelligence (AI), the Internet of Things (IoT) and Geographic Information Systems (GIS) offer innovative solutions through predictive analysis, real-time monitoring and spatial assessment. AI supports irrigation scheduling and soil moisture prediction, while IoT enables continuous monitoring of soil and environmental conditions using connected sensors. GIS and remote sensing facilitate watershed planning, soil erosion assessment and groundwater potential mapping. Integrating these technologies can improve irrigation efficiency, support soil conservation and promote informed agricultural decision-making. Their application is particularly relevant to water-scarce regions, including Gujarat. However, high implementation costs, limited connectivity, data reliability and inadequate technical expertise remain major challenges. Developing affordable, locally validated and farmer-friendly technologies is essential for promoting sustainable agricultural resource management.

**Keywords:** Artificial Intelligence, IoT, GIS, smart irrigation, soil conservation and water management.

## Introduction

Soil and water are essential natural resources for agricultural production, food security and environmental sustainability. However, groundwater depletion, soil erosion, irregular rainfall and increasing irrigation demand pose significant challenges to sustainable agriculture. These problems are particularly important in India, where agricultural productivity is strongly influenced by monsoon rainfall and irrigation availability. Conventional soil and water management practices often rely on fixed irrigation schedules and periodic field observations, which may not reflect changing soil moisture, weather conditions and crop water requirements. Excessive irrigation can cause water wastage, nutrient leaching and waterlogging, whereas insufficient irrigation can reduce crop productivity.

Recent developments in digital agriculture offer opportunities to address these challenges through Artificial Intelligence (AI), the Internet of Things (IoT) and Geographic Information Systems (GIS). AI supports predictive analysis and irrigation decisions, IoT enables real-time monitoring through connected sensors, and GIS combined with remote sensing provides spatial information for soil

conservation and watershed planning. Integrating these technologies can improve irrigation efficiency, support soil conservation and strengthen climate-resilient agriculture. This article discusses their applications, integration, challenges and future prospects, with particular reference to Indian agriculture.

**Role of Artificial Intelligence in Soil and Water Management**

Artificial Intelligence uses data from soil sensors, weather stations, satellites and historical records to support agricultural decision-making. Machine learning (ML), a branch of AI, can identify relationships between soil moisture, rainfall, temperature and crop water requirements (Gao *et al.*, 2023). AI-based irrigation scheduling: AI models estimate irrigation requirements using soil moisture, crop growth stages, evapotranspiration and weather forecasts. Unlike fixed schedules, these systems can recommend when and how much water should be applied, helping reduce unnecessary irrigation (Gu *et al.*, 2021). Soil moisture prediction: Machine learning models analyse previous moisture measurements, rainfall and temperature data to predict changes in soil water availability. These predictions can help identify potential water shortages and improve irrigation planning (*Gu et al.*, 2021). Drought assessment and water planning: AI can analyse climatic and soil-water information to identify potential water stress and support irrigation prioritization, particularly in rainfed and water-scarce regions. However, the effectiveness of AI depends on reliable data, locally calibrated models and affordable implementation.

**3. IoT-Based Smart Soil and Water Monitoring**

The Internet of Things enables continuous monitoring of agricultural conditions through interconnected sensors, communication networks and digital platforms. IoT systems can measure soil moisture, temperature and other environmental variables, helping farmers make timely irrigation decisions (Abdelmoneim *et al.*, 2025).

**Real-time soil moisture monitoring**: Capacitance, time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR) sensors measure soil water content. Their readings can be transmitted to mobile applications or cloud platforms, allowing farmers to monitor field conditions remotely. Appropriate sensor placement and soil-specific calibration are essential for reliable measurements (Datta & Taghvaeian, 2023).

**Automated irrigation:** IoT controllers can operate pumps and solenoid valves according to predefined soil moisture thresholds. Irrigation starts when moisture falls below the desired level and stops when sufficient moisture is restored. Integration with drip irrigation can improve water management and reduce manual intervention.

**Applications in India:** IoT-based systems can support irrigation management in cotton, groundnut and horticultural crops, including those cultivated in Gujarat. However, installation costs, connectivity, maintenance and technical training remain important barriers to adoption.

Overall, IoT provides the monitoring infrastructure needed for precision irrigation and efficient agricultural water use.

**GIS and Remote Sensing for Soil and Water Conservation**

Geographic Information Systems and Remote Sensing provide spatial information for monitoring land, water and soil resources. GIS integrates information on soil type, slope, rainfall, drainage and land use, while satellite observations help identify changes in vegetation, surface water and land cover (Singh *et al.*, 2023).

**Watershed management:** GIS-based analysis supports watershed delineation, drainage mapping and prioritization of areas requiring conservation measures. It can help identify suitable locations for check dams, contour bunds and rainwater harvesting structures.

**Soil erosion assessment:** GIS can combine rainfall, soil characteristics, slope, vegetation cover and land-use information to identify erosion-prone areas. Remote sensing helps monitor vegetation and land-cover changes, supporting targeted conservation planning.

**Groundwater potential mapping:** GIS-based models integrate geological, geomorphological, drainage and rainfall information to identify areas with potential for groundwater occurrence. These maps support preliminary planning, but field verification and hydrogeological assessment are necessary before selecting groundwater development or recharge sites (Arulbalaji *et al.*, 2019).

Thus, GIS and remote sensing support spatially informed soil conservation, watershed development and water resource planning.

**Integration of AI, IoT and GIS**

The integration of AI, IoT and GIS combines real-time monitoring, spatial analysis and predictive decision-making. IoT collects field data, GIS identifies spatial variations, and AI analyses these inputs to generate management recommendations.

**Precision irrigation:** Soil moisture sensors monitor root-zone water conditions, GIS identifies variations in soil and field characteristics, and AI models combine these observations with weather forecasts to estimate irrigation requirements. This approach can support site-specific water application and reduce unnecessary irrigation when properly calibrated (Abdelmoneim *et al.*, 2025).

**Intelligent soil conservation:** GIS and satellite data identify erosion-prone areas, while field sensors provide information on soil and environmental conditions. AI can analyse these datasets to support erosion-risk assessment and watershed prioritization.

**Farmer decision support:** Mobile applications and digital platforms can provide irrigation alerts, soil moisture information and conservation recommendations. Successful implementation requires reliable data, affordable equipment and locally validated models.

The combined use of these technologies offers a promising approach to climate-smart agriculture by improving resource-use efficiency and supporting informed management decisions.

**Applications in Indian Agriculture**

India faces challenges associated with groundwater depletion, irregular rainfall, soil degradation and inefficient irrigation. AI, IoT and GIS can support sustainable agricultural development through precision irrigation, soil monitoring and watershed planning.

**Smart irrigation**: AI and IoT can help farmers growing cotton, groundnut and horticultural crops in Gujarat monitor soil moisture and schedule irrigation according to crop requirements. Such systems can complement the Per Drop More Crop initiative, which promotes efficient water use through micro-irrigation.

**GIS-based watershed development:** Makwana and Tiwari (2016) demonstrated the application of remote sensing and GIS for prioritizing agricultural sub-watersheds in the semi-arid middle region of Gujarat. Similar approaches can assist in planning check dams, contour bunds and rainwater harvesting structures.

**Climate-resilient farming:** Satellite observations and GIS mapping can support the assessment of vegetation cover, agricultural land use and water availability. Integrating this information with IoT sensors and AI predictions could strengthen irrigation planning and watershed management.

These applications demonstrate the potential of digital technologies to improve soil and water management in Indian agriculture. Wider adoption will require farmer training, affordable equipment and region-specific solutions.

**7. Challenges and Future Prospects**

Despite their potential, AI, IoT and GIS face several challenges in agricultural applications. High initial costs, limited internet connectivity, insufficient technical knowledge and maintenance requirements can restrict adoption, particularly among small and marginal farmers. AI models require reliable datasets and local calibration, while IoT sensors need correct installation and regular maintenance. GIS assessments also depend on the accuracy and resolution of spatial data (Datta & Taghvaeian, 2023). Future developments in affordable sensors, low-power communication, cloud computing and machine learning may improve accessibility. Integrating mobile applications, automated irrigation and satellite monitoring could provide timely recommendations for efficient water use and soil conservation. Research should prioritize affordable technologies, field-level validation, farmer-friendly interfaces and quantitative evaluation of water savings, crop productivity and economic benefits.

**Conclusion**

AI, IoT and GIS offer promising opportunities for sustainable soil and water management in agriculture. AI supports irrigation prediction, IoT enables real-time monitoring, and GIS and remote sensing facilitate watershed planning, erosion assessment and water resource mapping. Their integration can improve irrigation efficiency, support soil conservation and strengthen climate-resilient farming. However, implementation costs, data reliability and technical limitations remain important challenges. Future efforts should focus on affordable, locally validated and farmer-friendly technologies to promote sustainable agricultural resource management in India.

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# NATURE-BASED SOLUTIONS FOR REDUCING SOIL EROSION AND ENHANCING SOIL CARBON SEQUESTRATION

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## Introduction

Soil is one of the most valuable natural resources supporting agricultural production, environmental sustainability and ecosystem functioning. It provides essential nutrients, water and physical support for plant growth while serving as an important reservoir of organic carbon. However, increasing agricultural intensification, deforestation, inappropriate land management and climate variability have accelerated soil degradation in many parts of the world. Soil erosion caused by water and wind removes fertile topsoil, reduces nutrient availability, deteriorates soil structure and adversely affects agricultural productivity. Furthermore, the loss of soil organic matter reduces the capacity of agricultural soils to store carbon and contributes to environmental degradation (Lal, 2004).

Nature-based solutions (NbS) have emerged as promising approaches for addressing soil erosion, land degradation and climate change through the protection, restoration and sustainable management of natural ecosystems. These solutions utilize vegetation, biological processes and ecological interactions to improve soil health and environmental resilience. Practices such as agroforestry, cover cropping, conservation agriculture, vegetative barriers, grassland restoration and organic matter management can help protect the soil surface, improve water infiltration and enhance soil organic carbon accumulation (IPCC, 2019).

Soil carbon sequestration refers to the process through which atmospheric carbon dioxide is absorbed by plants through photosynthesis and subsequently transferred into the soil through plant residues, roots and organic matter decomposition. A proportion of this carbon may remain stored in the soil for extended periods, depending on soil properties, climatic conditions and management practices. Increasing soil organic carbon improves soil aggregation, water-holding capacity, nutrient cycling and biological activity while contributing to climate change mitigation (FAO, n.d.; Lal, 2004).

The integration of nature-based solutions into agricultural landscapes provides opportunities to simultaneously reduce soil erosion and enhance carbon sequestration. By maintaining permanent or seasonal vegetation cover, improving soil structure and encouraging organic matter accumulation, these approaches can contribute to sustainable agricultural production and long-term environmental conservation. Therefore, adopting locally suitable nature-based solutions is increasingly important for protecting soil resources, improving ecosystem resilience and promoting climate-smart agriculture.

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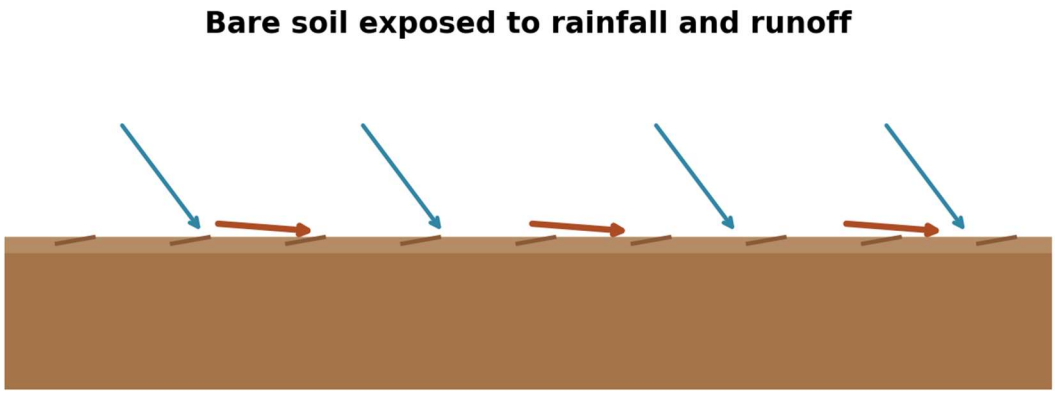



**Fig. 1. Exposed agricultural soil vulnerable to erosion by rainfall and surface runoff (schematic illustration)**

**Soil Erosion and Its Impact on Soil Carbon**

Soil erosion is the detachment, transportation and deposition of soil particles by natural agents, particularly water and wind. Agricultural lands are especially vulnerable when vegetation cover is removed, crop residues are burned or excessive tillage disturbs the soil surface. Rainfall impact breaks down soil aggregates, while surface runoff transports fine particles and organic matter away from agricultural fields. Wind erosion occurs mainly in dry regions where loose soil particles are exposed to strong winds.

The upper soil layer generally contains substantial quantities of organic matter, nutrients and microorganisms. Consequently, erosion can reduce soil fertility and redistribute organic carbon across the landscape. Although some eroded carbon may be buried and preserved in depositional environments, erosion often contributes to declining carbon stocks at affected agricultural sites. Soil degradation can also reduce plant growth and the return of organic residues to the soil (Lal, 2004).

Maintaining vegetation cover, improving soil aggregation and increasing organic matter inputs are therefore important strategies for reducing erosion and protecting soil carbon. The IPCC (2019) identifies cover crops, residue retention, reduced tillage and improved grazing management as effective options for addressing soil erosion and land degradation.

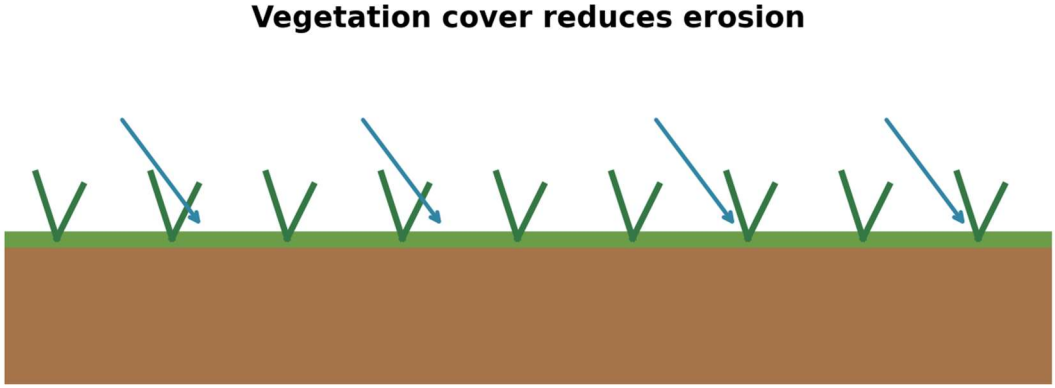



**Fig. 2. Protective vegetation cover reduces raindrop impact and soil movement (schematic illustration)**

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**Major Nature-Based Solutions For Soil Conservation**

*Agroforestry*: Agroforestry involves the deliberate integration of trees and shrubs with agricultural crops or livestock. Tree roots help stabilize soil, while canopies reduce rainfall impact and surface vegetation slows runoff. Leaf litter and root turnover also provide organic inputs that support soil carbon accumulation. Agroforestry systems can improve biodiversity, microclimatic conditions and agricultural resilience while providing additional products such as fruits, fodder and timber. The effectiveness of these systems depends on suitable tree species, planting arrangements and local environmental conditions (FAO, n.d.; IPCC, 2022).

*Cover Cropping*: Cover crops are grown primarily to protect and improve the soil rather than for direct harvest. Leguminous crops, grasses and other suitable vegetation provide surface protection during periods when agricultural land would otherwise remain bare. Their roots improve soil aggregation, while above-ground biomass reduces rainfall impact and surface runoff. Following termination, retained cover crop residues contribute organic matter and support soil biological activity. Cover cropping can therefore reduce soil erosion and support soil carbon sequestration over time (IPCC, 2019).

*Conservation Agriculture*: Conservation agriculture is based on minimizing soil disturbance, maintaining soil cover and diversifying crop species. Reduced or zero tillage helps limit mechanical disturbance, while residue retention protects the soil surface from erosion. Crop diversification can improve rooting patterns, nutrient cycling and biological activity. When implemented as an integrated system, these practices may improve soil structure and carbon retention, although outcomes vary according to climate, soil depth and management history (IPCC, 2019).

*Vegetative Barriers and Grass Strips*: Vegetative barriers consist of grasses, shrubs or other plants established along field boundaries, contours and erosion-prone slopes. These barriers reduce runoff velocity, trap transported sediments and protect agricultural land from further degradation. Deep-rooted perennial grasses can stabilize soil and contribute below-ground organic matter. Properly designed vegetative strips are particularly useful in sloping agricultural fields and regions experiencing intense seasonal rainfall.

**Restoration of Degraded Lands:** Restoration involves re-establishing vegetation and improving ecological functions in degraded landscapes. Native grasses, shrubs and trees can reduce exposure of bare soil, improve infiltration and gradually rebuild organic matter. Restoration practices should consider rainfall, soil characteristics, biodiversity and local land-use requirements. Long-term vegetation recovery can support carbon storage in both biomass and soil (IPCC, 2019).



**Fig. 3. Major nature-based soil conservation approaches: agroforestry, cover crops and vegetative barriers (schematic illustration)**

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**Role of Nature-Based Solutions in Soil Carbon Sequestration**

Soil carbon sequestration is an important ecosystem service associated with sustainable land management. Plants absorb atmospheric carbon dioxide through photosynthesis and convert it into organic compounds. A portion of this carbon enters the soil through fallen leaves, crop residues, root exudates and decomposing roots. Soil microorganisms transform these materials, and some carbon becomes associated with soil minerals or protected within soil aggregates.

Nature-based solutions can enhance this process by increasing organic carbon inputs and reducing losses associated with erosion and excessive soil disturbance. Agroforestry contributes carbon through tree litter and root biomass, while cover crops increase the duration of living plant cover and provide additional organic residues. Conservation agriculture and grassland restoration can also help protect soil organic matter and improve carbon cycling (Lal, 2004; IPCC, 2022).

The amount of carbon stored depends on soil texture, temperature, rainfall, vegetation type, management history and the duration of practice adoption. Importantly, soil carbon sequestration is not unlimited or permanent; accumulated carbon may be lost if vegetation is removed or soil management deteriorates. Therefore, long-term management and regular soil carbon monitoring are essential for evaluating actual sequestration benefits.

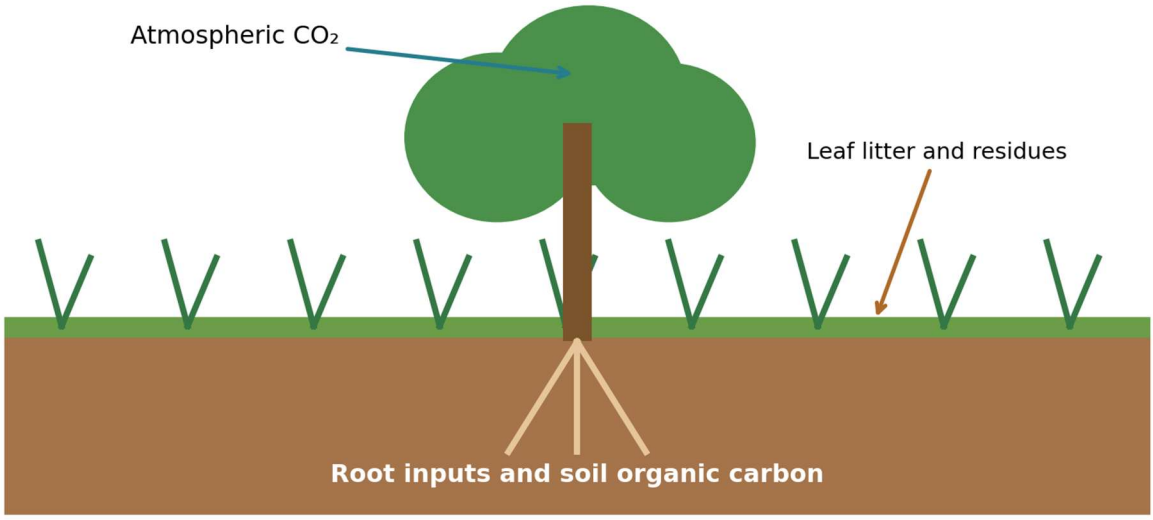



**Fig. 4. Conceptual pathway of soil carbon sequestration through photosynthesis, litter and root-derived organic inputs (schematic illustration)**

**Benefits of Nature-Based Solutions for Sustainable Agriculture**

Nature-based solutions provide multiple environmental and agricultural benefits beyond soil erosion control and carbon sequestration. Improved vegetation cover protects the soil from direct rainfall impact, reduces runoff and promotes water infiltration. Increased organic matter can improve soil aggregation, moisture retention and nutrient availability, supporting crop growth under variable climatic conditions.

These practices also contribute to biodiversity conservation by creating habitats for beneficial organisms and supporting biological activity within the soil. Agroforestry and diversified cropping systems may offer additional economic benefits through the production of fruits, fodder, timber and other agricultural products. Improved soil health can support long-term agricultural productivity and reduce vulnerability to drought and intense rainfall events (FAO, n.d.; IPCC, 2019).

For Indian agriculture, nature-based solutions are particularly relevant in rainfed farming regions, sloping agricultural lands and areas affected by declining soil fertility. Their successful adoption requires suitable species selection, farmer participation, technical guidance and long-term management.

**Challenges and Future Opportunities**

Despite their environmental benefits, nature-based solutions face several challenges during practical implementation. Limited farmer awareness, initial establishment costs, labour requirements, competition for land and water, and delayed economic returns may restrict adoption. In addition, the effectiveness of individual practices varies with soil type, rainfall distribution, cropping system and regional environmental conditions.

Measuring changes in soil organic carbon also requires reliable sampling, appropriate analytical methods and long-term monitoring. Short-term improvements in soil cover do not necessarily indicate equivalent increases in permanent soil carbon storage. Consequently, future research should focus on identifying region-specific combinations of nature-based practices, evaluating their long-term effectiveness and developing affordable monitoring approaches.

The integration of remote sensing, geographic information systems and soil monitoring technologies may support better assessment of vegetation cover, erosion risk and land restoration progress. Farmer training, institutional support and locally appropriate incentives can further encourage the adoption of sustainable soil management practices.

**Conclusion**

Nature-based solutions offer sustainable approaches for reducing soil erosion, improving soil health and enhancing soil carbon sequestration. Practices such as agroforestry, cover cropping, conservation agriculture, vegetative barriers and ecological restoration protect soil resources while supporting biodiversity and agricultural resilience. Their effectiveness depends on local conditions, appropriate management and long-term implementation. Integrating these approaches into agricultural systems can contribute to sustainable land management, climate change mitigation and the conservation of soil resources for future generations.

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# AUTOMATIC IRRIGATION USING SOIL-MOISTURE SENSOR

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**Abstract**

Water is one of the most important resources required for successful agricultural production. Conventional irrigation systems generally depend on fixed schedules or manual observation of soil conditions, which can result in over-irrigation, under-irrigation, water wastage and unnecessary energy consumption. To address these challenges, An automatic irrigation system based on soil-moisture sensing technology. The system continuously monitors moisture conditions in the crop root zone and automatically operates the irrigation pump according to predefined moisture limits. The proposed system combines a soil-moisture sensor, microcontroller, relay or contactor, water pump, filter, water tank and drip irrigation network. The system can also be upgraded with IoT-based monitoring and solar power to create a smart and sustainable irrigation solution.

**Introduction**

Efficient water management is essential for improving agricultural productivity and maintaining sustainable farming practices. In many farms, irrigation is carried out manually, where the farmer determines when to operate the pump based on visual observation, experience or a predetermined schedule. However, soil moisture can vary considerably depending on soil type, crop stage, weather conditions, temperature and evapotranspiration. Irrigating without considering the actual moisture condition of the root zone can therefore result in unnecessary water use or insufficient water availability to crops. Agricultural engineering technologies provide an opportunity to automate this process by using sensors and control systems.

The automatic irrigation system developed and designed to provide water according to the actual moisture requirement of the soil. A soil-moisture sensor installed near the crop root zone measures the moisture condition continuously. The sensor sends the information to a controller such as an

Arduino or ESP32. The controller compares the measured value with a predefined threshold and decides whether irrigation is required. When the soil moisture falls below the selected threshold, the controller activates the pump through a relay or contactor. Water is then delivered to the crop through a drip irrigation system. Once the required moisture level is reached, the controller switches the pump OFF automatically.

**Objective**

The main objective of this project is to design and develop a low-cost automatic irrigation system that can supply water according to crop and soil moisture requirements. The project also aims to reduce unnecessary water consumption, minimize manual intervention, improve irrigation efficiency and maintain a more stable moisture condition in the crop root zone. In addition, the project provides an opportunity for evaluate the application of sensors, automation and IoT technologies in practical agricultural production.

**System Design**

The proposed system consists of a water storage tank, pump, filter, irrigation pipes, drip lines, soil-moisture sensors, controller and switching mechanism. The soil-moisture sensor is positioned in the crop root zone so that it can represent the actual moisture condition experienced by the plants. The sensor output is connected to an Arduino or ESP32 controller. The controller processes the sensor signal and compares it with the programmed moisture threshold. A relay module or suitable motor contactor is used to control the irrigation pump. The pump supplies water from the storage tank through a filter and main pipeline to the drip irrigation network. The drip lines distribute water close to the plant root zone, reducing unnecessary water application.

**Working Principle**

The working principle of the system is based on feedback control. Initially, the soil-moisture sensor measures the moisture level of the soil. This information is continuously transmitted to the controller. If the measured moisture level is below the required range, the controller sends a signal to the relay or contactor to start the pump. Water is then supplied through the drip irrigation system. As irrigation continues, the soil moisture gradually increases. When the moisture reaches the programmed upper limit, the controller switches the pump OFF. The system then continues monitoring the soil until the moisture level again falls below the lower threshold. This automatic feedback cycle allows irrigation to take place according to actual soil conditions rather than a fixed time schedule.



**Example Moisture Control**

For prototype testing, an example threshold can be established in which soil moisture below 35% activates the pump, moisture between 35% and 60% is monitored, and moisture above 60% causes the pump to remain OFF. These values should not be treated as universal crop requirements. The appropriate threshold must be determined through sensor calibration and field testing according to crop type, soil characteristics, root-zone depth, climate and irrigation method.

**Experimental Setup at IGO Agritech Farm**

For experimental evaluation, We can establish two comparable plots using the same crop, soil type and general cultivation conditions. One plot can be maintained using conventional/manual irrigation and the second plot can use the automatic soil-moisture-based irrigation system. The automatic plot can be equipped with a water tank, filter, pump, drip irrigation lines, soil-moisture sensors and an Arduino or ESP32 controller. The experiment should be conducted over a defined crop-growth period, while irrigation, soil and crop parameters are recorded systematically. This arrangement allows the performance of the automatic system to be compared with conventional irrigation under similar field conditions.

**Data Collection and Performance Evaluation**

Several parameters can be measured during the experiment to evaluate the effectiveness of the system. Soil moisture should be recorded before and after irrigation to determine moisture stability. Daily water consumption can be measured using a flow meter or by accurately recording the volume supplied. Pump operating time and electricity consumption can also be recorded. Crop growth parameters such as plant height, number of leaves, biomass and final yield can be measured at suitable intervals. Labour requirements and irrigation operating costs should also be documented. These measurements can be used to determine water-use efficiency, energy consumption, labour requirements and economic performance.

**Manual and Automatic Irrigation Comparison**

The performance of the automatic irrigation system can be evaluated by comparing it with conventional irrigation. Important comparison parameters include daily water consumption, irrigation duration, pump operating time, electricity consumption, soil-moisture variation, labour requirement, irrigation cost and crop yield. Water-saving percentage can be calculated by comparing the quantity of water used by the conventional system with the quantity used by the automatic system. Similarly, energy and labour savings can be calculated from the recorded experimental data. Actual savings should be reported only after completing the field trial rather than using assumed values.

**IoT Integration**

The proposed system can be further developed into an IoT-based smart irrigation platform using an ESP32 or similar Wi-Fi-enabled controller. In the advanced version, sensor readings can be transmitted to a cloud platform or mobile dashboard. The farmer or farm management team can remotely monitor soil moisture, pump status, water flow, temperature and humidity. Alerts can also be generated when soil moisture becomes critically low, when abnormal water flow is detected or when the pump operates for an unusually long period. This approach can improve farm monitoring and support data-driven irrigation management.

| S.NO | COMPONENT | SPECIFICATION/EXAMPLE | FUNCTION |
|---|---|---|---|
| 1 | Soil Moisture Sensor | Capacitive type | Measures moisture level in soil |
| 2 | Arduino / ESP32 Controller | Microcontroller | Processes sensor data and controls irrigation |
| 3 | Relay / Contactor | Based on pump rating | Switches the pump ON/OFF |
| 4 | Water pump | According to field requirement | Pumps water from the tank |
| 5 | Water Tank | Suitable farm capacity | Stores irrigation water |
| 6 | Filter | Irrigation-grade filter | Prevents clogging of drip lines |
| 7 | Drip Irrigation Line | Crop-specific emitter spacing | Delivers water directly to the root zone |
| 8 | Flow sensor | Optional | Measures quantity of water supplied |
| 9 | Temperature & Humidity Sensor | Optional | Monitors environmental conditions |
| 10 | Solar panel | Optional | Provides renewable power |
| 11 | IoT / Wi-Fi Module | ESP32 / Wi-Fi | Enables remote monitoring |

**Solar-Powered Integration**

Solar energy can also be integrated into the automatic irrigation system to reduce dependence on conventional electricity. A solar panel can supply power to the controller and, depending on system design, to the irrigation pump through a suitable solar pumping and battery arrangement. Solar-powered operation is particularly useful for farms located in areas with good solar radiation. Combining solar energy with soil-moisture-based irrigation can create a system that addresses both water efficiency and renewable-energy utilization.

**Advantages**

The automatic irrigation system provides several potential advantages for Agritech Farm. It can reduce unnecessary irrigation by supplying water according to soil conditions, decrease the need for continuous manual pump operation and improve irrigation scheduling. Drip irrigation can deliver water close to the plant root zone, while sensor-based control can prevent irrigation when sufficient moisture is already present. The system can also provide a foundation for integrating IoT, solar power, fertigation and other precision-agriculture technologies. Because the system is modular, it can initially be implemented on a small experimental plot and later scaled according to field requirements.

**Limitations and Considerations**

The accuracy of the system depends strongly on proper soil-moisture sensor selection, installation and calibration. Different soil types can produce different sensor responses, and low-cost sensors

may require periodic calibration. Sensor placement is also important because a single sensor may not represent moisture conditions across a large field. Therefore, multiple sensors may be required for larger plots. The irrigation threshold should also be adjusted according to crop growth stage and soil characteristics. Proper electrical protection, waterproofing and pump safety measures are necessary for reliable field operation.

**Future Scope**

The Agritech Farm system can be further developed into a complete smart-farming platform. Future improvements may include multiple soil-moisture sensors, weather-based irrigation scheduling, automatic fertigation, flow-rate monitoring, solar-powered pumping, mobile notifications and cloud-based data analysis. Machine-learning techniques could also be explored in future research to predict irrigation requirements using historical soil moisture, weather and crop-growth data. Such developments can help transform the prototype into a scalable precision-irrigation system for different crops and farm sizes.

**Conclusion**

The automatic irrigation system using soil-moisture sensors represents a practical Agricultural Engineering application combining irrigation technology, sensors, electronics and automation. By continuously monitoring root-zone moisture and controlling irrigation according to predefined limits, the system can provide a more responsive approach to farm water management than fixed or purely manual irrigation scheduling. The proposed Farm project can be evaluated through controlled field experiments comparing manual and automatic irrigation. Measurements of water consumption, energy use, labour requirement, soil-moisture stability, crop growth and yield will provide the technical basis for assessing the system. With future integration of IoT, solar energy and automated fertigation, the project can be developed into a broader smart-farming solution for sustainable agricultural production.

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# PESTICIDE INDUCED PLANTHOPPER RESURGENCE IN RICE

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## Introduction

The term pest resurgence first appeared in the literature during the 1960s. Early occurrences of pest resurgence in planthoppers, especially the brown planthopper (BPH), *Nilaparvata lugens* Stal (Hemiptera: Delphacidae) were induced by insecticide applications (Chelliah, 1986). The definitions of resurgence emphasize insecticide-driven mortality of natural enemies because pest resurgence followed application of traditional insecticides such as organochlorines, organophosphates, carbamates and pyrethroids because it occurred in the F1 generations. Simultaneously, at sublethal doses most insecticides stimulate planthopper reproduction through a variety of physiological and molecular mechanisms. These two forces created an unusual ecological space that was ideal for pest population resurgence. The traditional insecticides were replaced by modern chemicals with improved human and environmental safety profiles (Guedes *et al.*, 2016), lower toxicity and reduced threat to natural enemies.

The planthoppers that feed on rice mainly consists of three species: BPH (*Nilaparvata lugens*), WBPH (*Sogatella furcifera)* and SBPH (*Laodelphax striatellus).* Both the nymphs and adults of these hoppers suck the sap from phloem and xylem resulting in drying up of the rice plant. Under field conditions, the damage by BPH and WBPH spreads in a circular fashion and is technically termed as “hopper burn.” Pesticide-induced rice susceptibility may benefit BPH feeding, survival, and reproduction (Wu *et al.*, 2001).

## Types of Resurgence

Based on time-related processes, resurgence is classified into two types, acute and chronic. The former is seen as a rapid resurgence in the F1 generation, driven by the traditional insecticides. The key features are high mortality of natural enemies coupled with stimulation of pest reproduction. Chronic resurgence is a relatively recent phenomenon associated with modern pesticides that are far less harmful to natural enemies but induce pest resurgence through physiological mechanisms that promote increased reproduction. This resurgence has relatively longer latency (F2 or later generations) following applications of agricultural chemicals. (Wu *et al.*, 2020).

## Factors contributing to Plant Hopper Resurgence:

### Impact of Pesticide Application on Natural Enemies

Rice agroecosystems are complex, composed of predators, parasites, parasitoids, herbivores and detritivores. Many of these animals provide valuable ecological services. Predators and parasitoids in particular are natural enemies of herbivorous pest insects. Agricultural chemicals challenge natural enemies in two ways, by killing some individuals and in surviving individuals, by sharply reducing their abilities to search for and locate pest eggs, larvae, pupae and adults. There are several factors that document the severe loss of biological control services due to pesticide application.

**Pesticides kill natural enemies**

Insecticides are lethal to natural enemies that can provide valuable biological control services. Triazophos and deltamethrin are lethal to the BPH egg predator *Cyrtorhinus lividipennis* (Zhang *et al.*, 2015) with deltamethrin causing 100% mortality. In addition to predatory insects, spiders are effective predators. Many insecticides kill spiders, leading to spider population declines and serious loss of spider-driven biocontrol services. Chen *et al*., (2017) tested toxicities of seven insecticides commonly used in rice fields on *Pardosa pseudoannulata* in laboratory experiments and reported that chlorpyriphos and abamectin are toxic to *P. pseudoannulata*.

**Reduction of natural enemy services due to pesticide exposure**

In addition to mortality, biocontrol services of surviving natural enemies decline substantially after exposure to agricultural chemicals. The mean prey consumption by *C. lividipennis* treated with sublethal concentrations of triazophos and separately deltamethrin decreased approximately 18–35% compared to controls (Xu *et al.*, 2000). Sublethal concentrations of triazophos, deltamethrin and imidacloprid stimulated reproduction of the predator *C. lividipennis*.

**Pesticides influence parasitoid behaviour and fecundity**

Parasitoid foraging capacity is influenced by sublethal doses of insecticides. In egg parasitoid, *A. nilaparvatae* consuming an imidacloprid–honey mixture led to substantial parasitism reduction, which involves sensory responses. Sublethal concentrations of triazophos and deltamethrin similarly operate through sensory physiology. Surviving parasitoids were unable to distinguish *N. lugens* –infested from non-infested plants (Liu *et al*, 2012). The reduction of the capacity of *A. nilaparvatae* to find host eggs for parasitization reduces the wasp's impact on pests.

**Influence of Pesticides on Physiology and Biochemistry of Rice Plants And Planthoppers**

Pesticide applications kill and otherwise impact targeted pests. Pests not killed by pesticide applications may suffer paralysis, substantial behavioral changes, feeding and foraging disorders and mating failures. Within the organisms, the applications lead to a range of changes at the physiological, biochemical and molecular levels.

**Pesticides influence rice physiology and biochemistry**

Oxalic acid (OA) is a dicarboxylic acid that acts in rice resistance to BPH. OA content is higher in planthopper-resistant rice varieties compared to susceptible ones. Some insecticides such as triazophos and imidacloprid lead to reduced OA content in rice. Buprofezin, imidacloprid and decamethrin lead to higher reduction of sugars (Wu *et al.*, 2003) and free amino nitrogen which benefits pests. Overexpression of glutathione-S transferase (GST) enhances plant resistance to stress.

**Pesticides influence plant hormones**

Pesticide-induced changes in plant hormones have the potential to drive changes at the whole-plant level. Cytokinins, including zeatins riboside (ZR), act in cell division and elongation and influence the intensity and direction of photosynthate flows. ZR content in rice leaves decreased significantly three days after separate foliar sprays with buprofezin, imidacloprid, and triazophos (Qiu *et al.*, 2004). These reports indicate that pesticides may inhibit ZR production or its upward systemic transport from roots to shoots.

**Pesticides influence rice gene transcription profiles**

Some pesticide-induced changes indirectly influence gene expression in rice. Cheng *et al.,* 2012 found 225 genes that were differentially expressed after an imidacloprid treatment; 117 were up-regulated, and 108 were down-regulated. Of these, specific expression of genes encoding plant lipid

transfer protein, lignin peroxidase, and flavonol-3-o-methyltransferenase was changed and this type of change may be responsible for the imidacloprid-induced rice susceptibility to BPH, which inflicted more damage on treated than control rice plants.

**Physiological and Biochemical Effects of Agricultural Chemicals on Planthopper Reproduction**

Juvenile hormone (JH) is a pleiotropic hormone with many actions in juvenile (*i.e.,* regulating developmental outcomes of molts) and adult (*i.e.,* promoting ovarian development) insects. Triazophos and deltamethrin treatments led to increased circulating JH-III titers in BPH females over 1–3 days postemergence (PE). The increased hormone titers are due to reduced levels of active JH esterase. (Ge *et al.*, 2010).

Insect vitellogenesis involves synthesis of yolk protein precursors in fat body, transport via haemolymph, and recognition and uptake by oocytes. Imidacloprid, triazophos and deltamethrin treatments led to increased protein contents, particularly vitellogenin, in BPH ovary and fat body (Hu *et al.*, 2010).

**Conclusion**

Despite the progress in developing target-focused insecticides, episodes of chronic resurgence continue to recur. The most urgent need is for further research on the physiological and molecular mechanisms and the results of such work need to be incorporated into resurgence models that link molecular mechanisms to ecological effects. This is a small step toward long-term, sustainable food and nutrition security for billions of humans.

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# BEGOMOVIRUSES INFECTING CUCURBIT CROPS

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**Abstract**

Begomoviruses (genus *Begomovirus*, family *Geminiviridae*) are important pathogens of cucurbitaceous crops, causing substantial yield and quality losses worldwide. Major cucurbit crops, including cucumber, melon, watermelon, pumpkin, squash, bottle gourd, bitter gourd and ridge gourd, are affected by begomovirus infections characterized by leaf curling, yellow mosaic, chlorosis, stunting, leaf distortion and fruit abnormalities. Among these viruses, Tomato leaf curl New Delhi virus (ToLCNDV) has emerged as a major threat to cucurbit production, with its geographical distribution expanding from the Indian subcontinent to parts of Asia, Europe and North Africa. Other important cucurbit-associated begomoviruses include Squash leaf curl virus, Cucurbit leaf crumple virus, Squash leaf curl China virus and Pumpkin yellow vein mosaic virus. Their spread is primarily mediated by the whitefly *Bemisia tabaci*, while host range expansion, genetic variability, recombination and movement of infected planting material contribute to disease emergence and dissemination. Accurate diagnosis is essential because begomovirus symptoms frequently overlap with those caused by other viral infections and abiotic stresses. Conventional PCR, rolling circle amplification, quantitative PCR, loop-mediated isothermal amplification (LAMP), lateral-flow detection and high-throughput sequencing provide complementary approaches for virus detection and characterization. Management strategies primarily involve integrated disease management, including resistant or tolerant cultivars, removal of infected plants and alternative hosts, healthy planting material, field sanitation and whitefly population management. Emerging molecular technologies, including RNA interference and gene editing, offer additional opportunities for developing resistant cucurbit cultivars. This review summarizes the global and Indian distribution of cucurbit-infecting begomoviruses, their symptoms, epidemiology, diagnostic approaches and management strategies, highlighting the importance of systematic surveillance and rapid detection in reducing disease-associated losses and limiting the further spread of these pathogens.

**Keywords**: Begomoviruses; cucurbits; Tomato leaf curl New Delhi virus; *Bemisia tabaci*; molecular diagnosis; epidemiology; integrated disease management.

## Introduction

Cucurbitaceous crops, including cucumber (*Cucumis sativus*), melon (*Cucumis melo*), watermelon (*Citrullus lanatus*), pumpkin, squash (*Cucurbita* spp.), bottle gourd (*Lagenaria siceraria*), bitter gourd (*Momordica charantia*), ridge gourd (*Luffa acutangula*) and sponge gourd (*Luffa cylindrica*), are affected by diverse viral pathogens causing mosaic, chlorosis, leaf curling, stunting and fruit abnormalities (Devendran *et al*., 2023). Among these, begomoviruses (genus *Begomovirus*, family *Geminiviridae*) are important whitefly-transmitted pathogens because of their broad host range, genetic variability and capacity for geographical expansion (Brown *et al*., 2015; Gambo *et al*., 2026).

Begomoviruses possess circular single-stranded DNA genomes and occur as monopartite or bipartite viruses; bipartite species contain DNA-A and DNA-B components (Brown *et al*., 2015). Their

evolution is driven by mutation, recombination and genomic reassortment, contributing to the emergence of genetically diverse populations and new host associations (Borah and Dasgupta, 2012; Brown *et al*., 2015). The principal vector, *Bemisia tabaci*, plays a major role in virus dissemination and disease development (Brown *et al*., 2015).

Among cucurbit-infecting begomoviruses, *Tomato leaf curl New Delhi virus* (ToLCNDV) has emerged as a major pathogen. Initially reported from tomato in the Indian subcontinent, it was subsequently detected in cucumber, bottle gourd and muskmelon (Ito *et al*., 2008). Its geographical range later expanded to Europe and North Africa, including Spain, Tunisia and Italy (Juárez *et al*., 2014; Mnari-Hattab *et al*., 2015; Panno *et al*., 2016), and subsequently to China (Gu *et al*., 2023).

The increasing diversity and geographical expansion of cucurbit begomoviruses emphasize the need for systematic surveillance and reliable molecular diagnosis. Conventional PCR and sequencing remain widely used, while LAMP and lateral-flow assays are being developed for rapid field detection (Venkataravanappa *et al*., 2020; Caruso *et al*., 2023; Qiao *et al*., 2026).

**International Scenario**

Globally, begomoviruses are increasingly recognized as important pathogens of cucurbit crops, with Tomato leaf curl New Delhi virus (ToLCNDV) being one of the most widely distributed cucurbit-infecting begomoviruses (Cai and Mei, 2023; Gambo *et al*., 2026). Originally reported from the Indian subcontinent, ToLCNDV has subsequently spread to several countries in Asia, Europe and North Africa, where it causes serious diseases in cucumber, zucchini, melon, watermelon and other cucurbits (Ito *et al*., 2008; Juárez *et al*., 2014; Mnari-Hattab *et al*., 2015). In Europe, ToLCNDV was first detected in Spain and later reported from Italy, where rapid dissemination occurred in zucchini-growing areas (Juárez *et al*., 2014; Panno *et al*., 2016; Panno *et al*., 2019). Other cucurbit-associated begomoviruses, including Squash leaf curl virus (SLCV) and Cucurbit leaf crumple virus (CuLCrV), are important in the Americas (Adkins *et al*., 2023). The international emergence of these viruses is associated with whitefly-mediated transmission, host expansion, genetic diversity and movement of infected plant material, emphasizing the need for global surveillance and rapid diagnostics (Borah and Dasgupta, 2012; Gambo *et al*., 2026).

**Indian Scenario**

In India, begomoviruses are important pathogens of cucurbit crops, with Tomato leaf curl New Delhi virus (ToLCNDV) being the most widely reported. It infects cucumber, watermelon, bottle gourd, muskmelon, ridge gourd, sponge gourd and other cucurbits, and is transmitted by *Bemisia tabaci* (Borah and Dasgupta, 2012; Nayaka *et al*., 2023). Other begomoviruses, including Tomato leaf curl Palampur virus (ToLCPalV) and Pumpkin yellow vein mosaic virus (PYVMV), have also been reported from cucurbit hosts in India (Muniyappa *et al*., 2003; Nayaka *et al*., 2023). Recent surveys have confirmed considerable geographical and host-associated diversity of begomoviruses in Indian cucurbits, emphasizing the need for continued surveillance and molecular characterization (Pradhan *et al*., 2025).

**Major Cucurbit Associated Begomoviruses**

| Begomovirus | Important cucurbit hosts/association | Major regions reported |
|---|---|---|
| *Tomato leaf curl New Delhi virus* | Cucumber, melon, watermelon, zucchini, pumpkin, bottle gourd, bitter gourd, sponge gourd and ridge gourd | South Asia, Southeast Asia, Mediterranean, Middle East, North Africa and China |

| Begomovirus | Important cucurbit hosts/association | Major regions reported |
|---|---|---|
| *Tomato leaf curl Palampur virus* | Cucumber, melon, pumpkin and other cucurbits | India, Iran and South Asia |
| *Pumpkin yellow vein mosaic virus* | Pumpkin and related cucurbits | India |
| *Squash leaf curl China virus* | Squash, pumpkin and other cucurbits | Asia, including India |
| *Squash leaf curl virus* | Squash, melon, watermelon and pumpkin | USA, Mexico and other regions |
| *Cucurbit leaf crumple virus* | Squash, cucumber, melon and other cucurbits | USA and Mexico |
| *Melon chlorotic leaf curl virus* | Melon and watermelon | Central America |
| *Mesta yellow vein mosaic virus* | Cucurbit-associated hosts | India |
| *Ageratum enation virus* | Cucurbit-associated hosts | India |
| *Pepper leaf curl Bangladesh virus* | Cucurbit-associated detections | India and South Asia |
| *Indian cassava mosaic virus* | Cucurbit-associated detection reported | India |

**Symptoms Associated with Cucurbit Begomoviruses**

Cucurbit begomovirus infections produce a wide range of symptoms that vary with the virus species, host genotype, infection stage and environmental conditions. The most commonly observed symptoms include leaf curling, yellowing, chlorosis, mosaic and mottling, often accompanied by vein clearing or vein thickening (Borah and Dasgupta, 2012; Cai and Mei, 2023). In ToLCNDV-infected cucumber, zucchini, melon and watermelon, severe infections may cause leaf distortion, blistering, reduced leaf size, stunting and shortening of internodes, resulting in considerable reduction in plant growth and productivity (Juárez *et al*., 2014; Panno *et al*., 2019). Infected plants may also exhibit flower and fruit abnormalities, including reduced fruit development, deformation and poor market quality (Cai and Mei, 2023). Symptoms associated with SLCV and CuLCrV commonly include chlorotic mosaic, leaf curling, vein clearing and crumpling, with severity increasing under high whitefly populations (Devendran *et al*., 2023). Because these symptoms can overlap with those caused by other viruses, nutritional disorders and environmental stresses, molecular confirmation is essential for accurate identification of the causal begomovirus (Nayaka *et al*., 2023).

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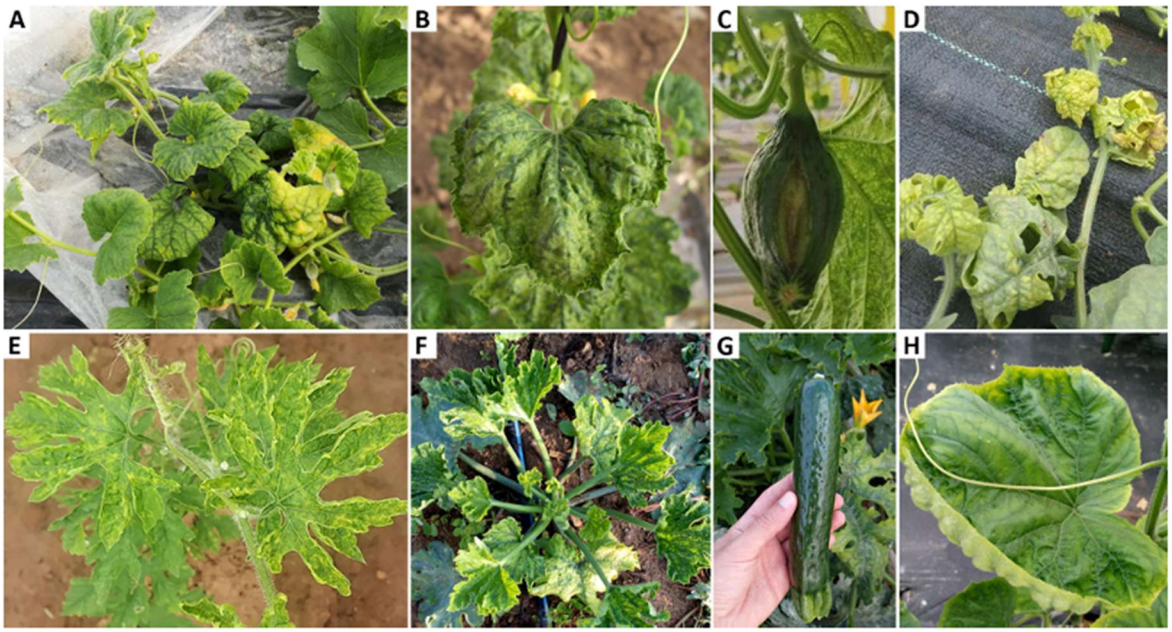



***Fig.1. Disease symptoms caused by Tomato leaf curl New Delhi virus in foliage and fruit of different cucurbit species. Yellowing and curling of melon (Cucumis melo) leaves (A, B), as well as fruit cracking (C). Watermelon (Citrullus lanatus) plants show yellowing and downward curling symptoms (D). Mosaic mottling with slight curling of leaves in bitter gourd (Lagenaria siceraria)(E). Short internodes and curling, vein swelling and mosaic symptoms in young zucchini (Cucurbita pepo) leaves (F). Zucchini fruits with lower marketability due to the roughness of the skin and reduced size (G). Yellowing and upward leaf curling on cucumber (Cucumis sativus) leaves (H).***

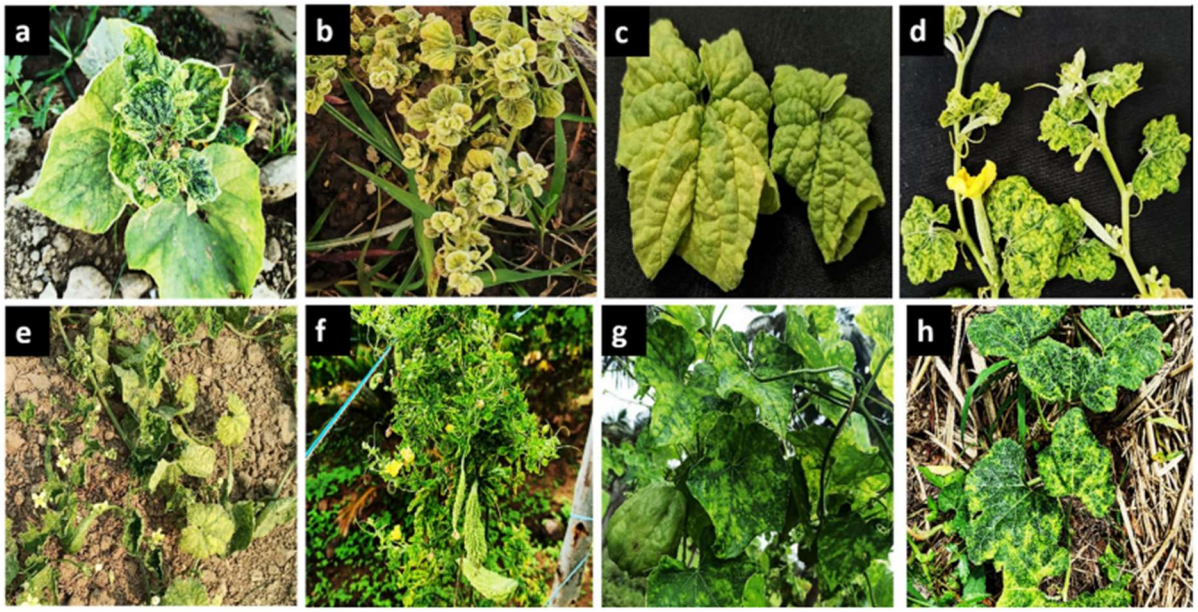



***Fig.2. Begomovirus disease symptoms observed in eight different cucurbits species across 12 locations from Haryana, Delhi, Uttar Pradesh, Chhattisgarh, Maharashtra, Telangana and Karnataka during sample collection; a: mosaic, leaf curl and stunting in cucumber; b: crinkle leaves, leaf curl and stunting in bottle gourd; c: yellow mosaic and leaf puckering in muskmelon; d: mosaic, leaf puckering and leaf curl in sponge gourd; e: leaf curl, puckering and fruit deformation in ridge gourd; f: leaf curl, mosaic and deformed fruit in bitter gourd; g: mosaic and fruit deformation in chayote and h: leaf puckering and yellow mosaic in pumpkin***

**Vector and Epidemiology**

Cucurbit-infecting begomoviruses are primarily transmitted by the whitefly *Bemisia tabaci* in a persistent, circulative and non-propagative manner, making the vector a major determinant of virus spread and disease development (Cai and Mei, 2023; Navas-Castillo *et al*., 2011). In particular, ToLCNDV is efficiently transmitted by *B. tabaci*, and transmission efficiency can vary with the whitefly cryptic species and host plant (Sánchez-Campos *et al*., 2022). Recent Indian studies demonstrated efficient transmission of ToLCNDV by the Asia I cryptic species of *B. tabaci* in bitter gourd, ridge gourd and pumpkin, with transmission observed even after short acquisition and inoculation access periods (Sivagnanapazham *et al*., 2025).

The epidemiology of cucurbit begomoviruses is influenced by whitefly abundance, availability of infected hosts, continuous cultivation of susceptible crops, alternative weed or crop hosts and environmental conditions. High vector populations can facilitate rapid secondary spread within fields, while successive or overlapping cucurbit cultivation can maintain virus sources and favour disease establishment (Cai and Mei, 2023). The geographical expansion of ToLCNDV, particularly into Mediterranean and other regions, demonstrates the importance of vector-mediated dissemination in the emergence of cucurbit begomoviruses (Sánchez-Campos *et al*., 2022).

Although whitefly transmission is the major epidemiological pathway, seed-associated transmission has also been reported for some ToLCNDV–cucurbit combinations, suggesting a possible additional route for long-distance dissemination and introduction into new production areas (Kil *et al*., 2020). Therefore, understanding virus–vector interactions, monitoring *B. tabaci* populations and detecting infected planting material are important components of cucurbit begomovirus epidemiology and disease management.

**Diagnostic Approaches**

Accurate diagnosis of cucurbit-infecting begomoviruses is essential because their symptoms often overlap with those caused by other viruses and abiotic stresses. PCR-based assays, particularly conventional PCR using begomovirus-specific primers, are widely used for initial detection and species identification (Nayaka *et al*., 2023). Rolling circle amplification (RCA) is useful for amplifying the circular ssDNA genomes of begomoviruses and facilitates subsequent restriction analysis, cloning and sequencing (Inoue-Nagata *et al*., 2004). Real-time PCR (qPCR) provides greater sensitivity and quantitative detection and is useful for samples with low virus titre (Cai and Mei, 2023).

For rapid and field-level diagnosis, loop-mediated isothermal amplification (LAMP) has been developed for ToLCNDV and can detect infection without conventional thermal cycling equipment (Venkataravanappa *et al*., 2020; Caruso *et al*., 2023). More recently, LAMP coupled with lateral-flow detection has enabled rapid visual confirmation of ToLCNDV amplification products, improving its suitability for on-site testing (Qiao *et al*., 2026). High-throughput sequencing (HTS) and metagenomic approaches provide a broader strategy for detecting known and emerging begomoviruses, identifying mixed infections and characterizing viral diversity (Cai and Mei, 2023). Thus, diagnostic methods have progressed from conventional PCR and sequencing towards sensitive, rapid and field-deployable molecular platforms, which are particularly valuable for surveillance and early detection of emerging cucurbit begomoviruses.

**Management of Cucurbit Begomoviruses**

Management of cucurbit begomoviruses is challenging because there are no effective curative treatments once plants become systemically infected. Therefore, management primarily relies on integrated approaches targeting the virus, its whitefly vector and sources of infection (Borah and Dasgupta, 2012; Cai and Mei, 2023). Removal of infected plants, control of volunteer plants and weeds, use of healthy planting material and maintenance of field sanitation can reduce primary virus sources and secondary spread (Cai and Mei, 2023). Management of *Bemisia tabaci* through suitable insecticides, reflective mulches, physical barriers and biological control can further reduce virus transmission; however, insecticide resistance in whitefly populations makes sole dependence on chemical control unreliable (Navas-Castillo *et al*., 2011). Host resistance is considered an important sustainable strategy, and screening of melon, cucumber and other cucurbit germplasm has identified sources of resistance or tolerance to ToLCNDV (Sáez *et al*., 2017; Pérez-Moro *et al*., 2024). Cultural practices such as crop rotation, removal of crop residues, weed management and adjustment of planting time can also help reduce vector pressure and disease development (Cai and Mei, 2023). More recently, RNA-based technologies, gene editing and RNA interference (RNAi) have been investigated as potential approaches for developing begomovirus-resistant cucurbit cultivars, although their field-level application requires further validation (Gambo *et al*., 2026). Consequently, an integrated management strategy combining resistant cultivars, clean planting material, vector management, field sanitation and early molecular detection offers a practical approach for reducing losses caused by cucurbit begomoviruses.

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# BIOFUMIGATION: TURNING CROP RESIDUES INTO A SOIL DISEASE-FIGHTING TOOL

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**Abstract**

Soil-borne plant pathogens are major constraints to agricultural productivity because they can persist in soil and crop residues for extended periods, making their management difficult. The environmental and health concerns associated with conventional chemical fumigants have increased interest in sustainable alternatives, including biofumigation. Biofumigation primarily involves incorporating plant materials, particularly those belonging to the Brassicaceae family, into soil to release biologically active compounds during decomposition. Glucosinolates present in these plants are hydrolysed by the enzyme myrosinase, producing isothiocyanates (ITCs) and other compounds with antimicrobial and nematicidal properties. Biofumigation has demonstrated potential against several soil-borne pathogens, including *Fusarium*, *Rhizoctonia*, *Verticillium*, *Phytophthora* and plant-parasitic nematodes. However, its effectiveness varies according to plant species, chemical composition, soil conditions, application methods and pathogen susceptibility. This article examines the mechanisms, applications, benefits and limitations of biofumigation and highlights its role in integrated soil-borne disease management.

**Keywords:** biofumigation, brassicaceae, glucosinolates, isothiocyanates, soil-borne pathogens

## Introduction

Soil-borne plant pathogens are responsible for substantial crop losses worldwide. Organisms such as *Fusarium* spp., *Rhizoctonia solani*, *Pythium* spp., *Phytophthora* spp. and *Verticillium* spp., together with plant-parasitic nematodes, can survive in soil or infected plant residues and cause diseases including root rot, damping-off, vascular wilt and root-knot disease. Their persistence and concealed location make effective management particularly challenging. Although chemical soil fumigation has traditionally been used to suppress these organisms, concerns about environmental contamination, human health, non-target effects and regulatory restrictions have encouraged the development of alternative approaches (Panth *et al*., 2020; Gullino *et al*., 2022).

Biofumigation has emerged as a promising component of sustainable disease management. It involves incorporating plant-derived materials into soil to release compounds capable of suppressing soil-borne pathogens and pests. Brassicaceae crops, particularly mustard, rapeseed, broccoli and related species, are widely investigated because of their glucosinolate content. These compounds can generate biologically active products during tissue decomposition. Nevertheless, biofumigation is not universally effective, and its practical value depends on the interaction between plant chemistry, soil conditions, pathogen biology and management practices (Hanschen & Winkelmann, 2020).

## Mechanism of Biofumigation

The principal mechanism of Brassica biofumigation involves the breakdown of glucosinolates into biologically active compounds, particularly isothiocyanates. Glucosinolates are sulfur-containing

secondary metabolites naturally present in Brassicaceae plants. In intact tissues, glucosinolates and the enzyme myrosinase are stored separately. When plant tissues are chopped, crushed or macerated, these components come into contact, initiating enzymatic hydrolysis. Depending on the glucosinolate structure and environmental conditions, this process produces ITCs and other degradation products.

Isothiocyanates can interfere with essential cellular functions in susceptible microorganisms, including membrane integrity, enzyme activity and metabolic processes. Their antimicrobial activity has been demonstrated against several fungal pathogens under laboratory conditions (Plaszkó *et al*., 2021). However, the concentration of glucosinolates in plant material alone does not determine treatment effectiveness. The efficiency of tissue disruption, myrosinase activity, soil moisture, temperature and the persistence of ITCs also influence pathogen exposure.

Biofumigation may additionally suppress pathogens through indirect biological processes. Incorporation of plant residues supplies organic carbon and nutrients, stimulating microbial activity and changing soil microbial community composition. These changes may favor microorganisms that compete with or antagonize pathogens. Research has documented interactions between Brassica biofumigants and soil microbiota, although the contribution of these microbial changes to disease suppression varies among systems (Tagele *et al*., 2021). Thus, biofumigation operates through a combination of direct chemical effects and changes in the soil environment.

**Biofumigation Materials and Target Pathogens**

Several Brassicaceae species have been investigated as biofumigant crops, including *Brassica juncea* (Indian mustard), *B. napus* (rapeseed), *B. carinata*, *B. oleracea* and *Raphanus sativus* (radish). Their effectiveness depends on glucosinolate composition, biomass production and the capacity of the plant material to release active compounds during decomposition. In addition to green manures and crop residues, processed seed meals have attracted interest because their application rates and chemical characteristics may be more readily standardized.

Fungal pathogens are among the most extensively studied targets. Brassica-derived ITCs have demonstrated inhibitory activity against several *Fusarium*, *Rhizoctonia* and *Verticillium* species in laboratory and controlled-environment experiments. However, laboratory inhibition does not necessarily translate into reliable field-level disease control. Ashiq *et al*. (2022), for example, investigated Brassicaceae biofumigation against *Fusarium graminearum* in a wheat–maize rotation. Although some treatments reduced pathogen DNA, significant suppression of maize ear and stalk rot was not achieved under the experimental conditions. This finding demonstrates that reductions in pathogen abundance do not automatically result in measurable disease control.

Oomycetes, including *Pythium* and *Phytophthora*, are also potential targets. Brassica-derived compounds have shown activity against these organisms, and processed seed meals have been investigated as alternatives to conventional soil fumigants. In particular, defatted *Brassica carinata* seed meals have been evaluated for managing *Phytophthora nicotianae* in pepper production. However, their effectiveness depends on the formulation, application conditions and susceptibility of the target organism.

Plant-parasitic nematodes, particularly root-knot and lesion nematodes, represent another important target group. Certain ITCs possess nematicidal properties, and laboratory investigations have demonstrated activity against nematodes such as *Pratylenchus penetrans* (Chekanai *et al*.,

2024). Nevertheless, field performance depends on whether nematodes encounter sufficient concentrations of active compounds within the soil profile. The suitability of the biofumigant crop as a host for the target nematode must also be considered.

Overall, the evidence supports the potential of biofumigation against several economically important soil-borne organisms, but its effectiveness varies among pathogens and production systems. It should therefore be selected according to the target pathogen rather than applied as a universal soil-disinfestation treatment.

**Factors Affecting Biofumigation Efficacy**

The effectiveness of biofumigation is influenced by plant characteristics, soil properties and management practices. Plant species and cultivar are particularly important because glucosinolate concentrations and profiles vary considerably. Biomass quantity also affects the potential release of active compounds, although high biomass does not necessarily guarantee greater pathogen suppression.

Effective tissue disruption and rapid incorporation are important for promoting glucosinolate hydrolysis. Soil moisture influences enzymatic activity, decomposition and the movement of bioactive compounds, while temperature affects both the rate of decomposition and the persistence of ITCs. Soil texture, organic matter, pH and microbial activity can further influence the availability and degradation of these compounds.

Application timing is equally important. If the interval between incorporation and planting is insufficient, residual compounds may inhibit seed germination or damage young roots. Conversely, excessive delays may allow active compounds to dissipate before adequate pathogen exposure occurs. Therefore, appropriate crop selection, biomass management, incorporation methods and planting intervals are essential for obtaining consistent results (Hanschen & Winkelmann, 2020; Ji *et al.*, 2024).

**Benefits and Limitations**

Biofumigation offers several potential advantages for sustainable agriculture. It can reduce populations of susceptible soil-borne pathogens, provide an alternative source of disease-suppressive compounds and utilize cover crops or crop residues within existing rotations. Incorporation of plant biomass may also contribute organic matter and influence soil biological activity. Under suitable conditions, biofumigation may reduce dependence on synthetic soil fumigants and complement other environmentally conscious crop-management practices.

However, biofumigation has important limitations. Its efficacy is variable, and the concentrations of active compounds generated in soil are often difficult to predict. Producing sufficient biomass may require additional land, water, time and machinery. Furthermore, biofumigation can affect beneficial soil microorganisms as well as pathogens because ITCs are biologically active compounds rather than selectively targeted pesticides. Changes in microbial community composition therefore require careful evaluation, particularly when treatments are repeated over several cropping cycles (Tagele *et al*., 2021).

Phytotoxicity, inconsistent field performance and economic constraints may also restrict adoption. Biofumigation should not automatically be considered equivalent to chemical fumigation, which may provide broader and more predictable soil disinfestation under appropriate conditions. Its practical value must instead be evaluated according to the crop, target pathogen, local environment and total production costs.

**Integration with Disease Management and Recent Developments**

Biofumigation is most appropriately used as part of integrated soil-borne disease management. Crop rotation can interrupt pathogen multiplication, while resistant cultivars reduce disease development where effective resistance is available. Biological control agents and suppressive organic amendments may complement biofumigation by influencing pathogen survival and soil microbial interactions. Soil solarization and biosolarization can also be considered where climatic and production conditions are suitable.

Anaerobic soil disinfestation is another complementary approach, although it differs mechanistically from conventional Brassica biofumigation. It relies on incorporating organic substrates and creating oxygen-depleted soil conditions that suppress susceptible pathogens. Combinations of these approaches may improve disease management, but their effectiveness should be confirmed through field trials rather than assumed.

Research increasingly emphasizes the importance of soil microbial communities, plant chemical profiles and standardized biofumigant formulations. Studies of Brassica biofumigation have explored how treatment-induced microbial changes relate to pathogen suppression, while recent reviews have highlighted the need to optimize plant materials and application conditions (Ji *et al*., 2024; Li *et al*., 2024). Research further examined microbiome-associated suppression of Fusarium wilt following broccoli-residue biofumigation (Wang *et al*., 2026). These findings support continued investigation of interactions between bioactive compounds and soil ecology, although their reproducibility across different soils and cropping systems requires further evaluation.

Important research priorities include developing standardized application protocols, measuring actual ITC concentrations in soil, identifying effective cultivars, assessing non-target effects and conducting long-term field and economic studies. Greater understanding of these factors would help improve the consistency and practical applicability of biofumigation.

**Conclusion**

Biofumigation is a promising biological approach for managing selected soil-borne plant pathogens. Its principal mechanism involves the production of isothiocyanates from glucosinolates in Brassicaceae materials, supplemented by changes in soil microbial activity and physicochemical conditions. Experimental evidence supports activity against several fungal pathogens, oomycetes and plant-parasitic nematodes, but field efficacy remains variable.

The success of biofumigation depends on appropriate plant selection, biomass production, tissue disruption, soil conditions, application timing and pathogen susceptibility. Further research is required to improve standardization, establish long-term benefits and assess economic feasibility. Rather than being considered a universal replacement for chemical fumigation, biofumigation should be integrated with crop rotation, resistant cultivars, biological control and other appropriate management practices. Its greatest contribution to sustainable crop production will depend on translating its demonstrated biological potential into reliable and economically viable field applications.

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# BIOPRIMING: A SMART AND ECO-FRIENDLY STRATEGY FOR PROTECTION OF CROPS FROM BIOTIC AND ABIOTIC STRESSES

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## Introduction

Today's agriculture is confronted with several issues. Farmers face erratic rainfall, rising temperatures, drought, floods, decreased soil fertility and more frequent pest and disease outbreaks. Climate change is only exacerbating these difficulties, making crop production harder than ever. Even though the chemical fertilisers and pesticides have helped in improving the production over the years, but their overuse has emerged as new challenges such as soil deterioration, environmental pollution, and outbreak of resistant pests and viruses. Thus, it is becoming increasingly necessary to adopt green and sustainable farming approaches that could boost crop yield without any harm to the environment. One of the promising technologies is biopriming, a simple seed treatment technology that boosts plants from the very beginning of their life cycle and supports them to overcome both biological and environmental obstacles.

## What is Bio-priming?

Biopriming is a seed treatment technique in which the seeds are coated or treated with beneficial microorganisms prior to sowing. After treatment, the seeds are stored under wet conditions for a short duration, so that the helpful microorganisms could multiply on the surface of the seed. The seeds are further dried in the shade and then sown in the field. Once the seed starts to grow, these microbes colonise the growing roots and begin to defend the new seedling from hazardous pathogens in the soil. At the same time, they stimulate root growth, boost nutrient absorption and promote healthy plant development. In other words, biopriming provides the seed with a natural coat of armour during the most vulnerable stage and thus maintaining its quality parameters.

## Why is Biopriming Important?

Healthy seed germination and strong seedling growth are the first steps toward the success of any crop. Immediately after sowing, even high-quality seeds may not establish well if they are subjected to extreme conditions of illnesses, poor soil conditions, nutrient deficiencies, or moisture stress. Weak seedlings often lead to poor crop stand and reduced yields. Bioprimed seeds overcome these challenges by maintaining the seed quality parameters thereby enhancing seed germination, increasing seedling vigour and stimulating the establishment of a stronger root system. Healthy seedlings get established faster, are more effective in uptaking water and nutrients, and better able to cope with the different challenges during the crop growth season. That means healthier crops for farmers with less dependence on chemical inputs.

## Beneficial Microbes and Biopriming

The effectiveness of biopriming mostly relies on the helpful bacteria applied for seed treatment. *Trichoderma* is one of the most used beneficial fungi that is known to reduce fungal diseases transmitted by soil. It competes with pathogenic microbes for space and nutrition and produces

enzymes which eradicate disease-causing infections to protect plant roots. In addition, *Trichoderma* promotes root growth and improves nutrient intake, resulting in stronger plants. Another popular microorganism is *Pseudomonas fluorescens* that produces natural antibiotics to inhibit numerous plant diseases. It also produces plant growth stimulating chemicals, which encourage rapid root growth and enhance the plant's natural defence system. Species of *Bacillus*, especially *Bacillus subtilis* and *Bacillus amyloliquefaciens* are of comparable importance since they produce antimicrobial chemicals, increase nutrient availability and overall plant growth. For pulse crops such as chickpea, soybean, pea, lentil and pigeon pea, *Rhizobium* bacteria are used to fix atmospheric nitrogen in root nodules, thus decreasing the need for nitrogen fertilisers. *Azotobacter* and *Azospirillum* both fix nitrogen and produce plant growth hormones to benefit non-leguminous crops. Another important group is the mycorrhizal fungi, which develop a beneficial relationship with plant roots and greatly boost the uptake of phosphorus, water and other nutrients, especially under drought conditions.

**Biopriming: How Does It Protect Crops from Diseases?**

Biopriming has the most potential to prevent biotic stresses, which are generated by living organisms such as fungi, bacteria, viruses, nematodes and insects-pests. Soil-borne fungal infections are particularly detrimental during seed germination and early seedling development. Diseases include damping-off, root rot, collar rot, wilt and seedling blight usually harm young seedlings before they could be established resulting in poor plant population and enormous productivity losses. Beneficial microorganisms employed in biopriming protect plants by several natural ways. As soon as treated seeds are sown, these bacteria quickly colonise the seed surface and the surrounding root zone. They take up the available space and use the nutrients, preventing hazardous organisms from getting a foothold around the roots. This natural competition greatly minimises disease infection. Many useful microbes also create natural antibiotics and antimicrobial substances that directly hinder the growth of dangerous fungus and bacteria. Some bacteria produce specific enzymes that break down the cell walls of harmful fungi and so avoid infection. These mechanisms occur naturally and are therefore an environmentally friendly alternative to frequent treatments of artificial fungicides. Another key benefit of biopriming is that it activates the plant's own defence mechanism such as Induced Systemic Resistance (ISR).

Biopriming has been successfully used in a wide variety of crops including cereals like rice, wheat, maize, sorghum and pearl millet, pulses like chickpea, lentil, green gram, black gram and pigeon pea, oilseed crops like mustard, soybean, sunflower and groundnut, vegetables like tomato, chilli, brinjal, cabbage, cauliflower, onion and okra, cotton and several spice crops. Evidence from diverse agro-climatic locations indicated that bioprimed seeds germinate more uniformly, grow stronger root systems, have fewer disease issues and ultimately generate larger yields than untreated seeds.

**Biopriming for Managing Abiotic Stress**

Beside protecting crops from illnesses, biopriming also helps plants survive abiotic pressures induced by unfavourable environmental circumstances rather than living organisms. Some of the most important abiotic factors that affect agriculture today are drought, salinity, high and low temperatures, waterlogging, nutrient inadequacy and heavy metal poisoning. These stressors limit seed germination, impede plant growth, decrease photosynthesis and ultimately impair agricultural output. As extreme weather events are becoming more frequent due to climate change, managing abiotic stress has become a serious concern for farmers. "Bioprimed seeds have a better chance of

tolerating these harsh conditions as the beneficial microorganisms associated with the seeds improve plant health in various ways. They promote root growth, increase nutrient intake, enhance water absorption, and produce natural compounds that assist plants cope with stress. Thus, bioprimed plants are healthier and flourish even in harsh environmental situations.

**Enhancing Drought Tolerance:** Drought is one of the main constraints for agricultural productivity around the world. Crop moisture stress is primarily caused by the deficit of rainfall and the decrease in ground water levels particularly during the critical phases of crop development. Biopriming with beneficial microbes promotes the development extensive root systems, aiding plants cope with drought stress. Many beneficial bacteria also produce natural hormones such as auxins, gibberellins and cytokinins which promote root growth and enhance plant development. Bioprimed crops are seen to have better growth, wilt later and have higher yield under drought stress than unprimed crops.

**Mitigation of Soil Salinity:** Another important concern influencing agricultural output, especially in dry and semi-arid countries, is soil salinity. High salt levels affect the plant's ability to uptake water and nutrients, resulting in poor germination, stunted growth, leaf burn and reduced yield. Biopriming enhances mineral nutrient balance and mitigates the negative effects of excess sodium ions, which enables plants to endure saline conditions. Some of the beneficial bacteria create enzymes like ACC deaminase which reduces the stress ethylene level in the plants. Excess ethylene is commonly produced during stress circumstances and limits root growth. These microbes reduce the production of ethylene, allowing roots to flourish in saline soils. Salt-tolerant plants operate normally under salt stress because of improved root growth and increased nutrient uptake.

**Protection from heat and cold stress:** Climate change has made extreme temperatures more common. High temperatures injure cells in plants and limit photosynthesis, and they also increase water loss through transpiration. Germination at low temperatures can also be delayed, enzyme activity reduced and crop establishment affected. The beneficial microorganisms used in biopriming allow plants to resist temperature stress by enhancing the antioxidant activity and keeping the cells of plants stable. These bacteria trigger the synthesis of defensive chemicals that minimise damage by dangerous molecules known as reactive oxygen species. They also enhance the plant's hydration status and metabolic activity, helping crops to bounce back faster during spells of excessive heat or cold. Thus, the bioprimed plants generally display enhanced growth and survival under varying temperature circumstances.

**Nutrient use efficiency:** Nutrient shortage is another key abiotic factor impacting the crop productivity. Many soils have nutrients that are not available to plants in insoluble forms. The beneficial microorganisms used in biopriming breakdown phosphorus, mobilise potassium, fix atmospheric nitrogen and release micronutrients that are easily absorbed by plants. Improved nutrient availability not only improves plant development, but also the effectiveness of applied fertilisers. Therefore, farmers can cut fertiliser inputs while sustaining optimum crop output. This will lower the expenses of manufacturing and reduce the degradation of the environment with excessive use of fertilisers.

**How Biopriming Works inside the Plant**

The success of biopriming is in the strong contact developed between helpful microbes and plant roots. After the seeds have germinated, these bacteria colonise the rhizosphere, the small region of

soil directly influenced by the roots. They secrete growth stimulatory chemicals, vitamins, enzymes and organic acids which enhance the availability of nutrients and stimulate root development. Bioprimed plants also produce increased levels of antioxidants, osmoprotectants and stress-responsive proteins that protect cells from environmental damage. These chemicals are responsible for maintaining the cell structure, the photosynthetic activity and the water balance during stressful situations. In this way biopriming reinforces the natural defence system of the plant against biotic and abiotic stresses without depending much on chemical inputs.

**Biopriming Limitations**

Biopriming has many advantages, but its success depends on its correct application. The effectiveness of the microbial inoculants is important, because ineffective or contaminated solutions may not bring the desired benefits. Farmers are advised to always use certified bioinoculants from recognised manufacturers and to follow the approved seed treatment protocols. Biopriming efficiency is also influenced by environmental conditions. Very dry soils, very wet soils or unfavourable temperatures may reduce the survival of the beneficial microbes after sowing. Moreover, treated seeds are generally not suitable for long-term storage and should be seeded within the prescribed period for maximal microbial activity. Therefore, the bioinoculants must be applied and stored carefully to be able to obtain effective results.

**What's Next?**

The use of biopriming is becoming increasingly popular as the agricultural sector moves towards more sustainable and climate-resilient production systems. Scientists are continually finding new kinds of helpful microbes that help crops better resist all kinds of threats. More sophisticated formulations are under development that contain several compatible micro-organisms, to try to provide wider protection against diseases and environmental stresses. Future research will likely focus on crop-specific microbial consortia, improved bioformulations and delivery technologies to improve the survival and effectiveness of beneficial microbes in the field. With the increased awareness amongst farmers and the availability of biopinoculant technologies, biopriming is likely to become an integral component of integrated crop management programs.

**Conclusion**

Modern agriculture requires the innovation to increase productivity, while being prudent in the use of natural resources. Biopriming has been widely accepted as a very promising biological seed treatment technology for its ability to enhance seed germination, seedling vigour, root growth and protect crops from biotic and abiotic stresses. Biopriming uses the advantages of natural micro-organisms to reduce the need for chemical pesticides and fertilisers and encourage healthier soils and more robust crops. Biopriming is not a complete replacement for all crop protection techniques, but it is an important component of sustainable agriculture. With climate change posing bigger challenges to the global agriculture, the use of simple and eco-friendly technology such as biopriming can help the farmers to grow healthy crops while saving the environment for the future generations.

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# MITES IN AGRICULTURE: HOW TO RECOGNIZE THEM AND THEIR DAMAGE

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**Abstract**
Mites are among the smallest animals that feed on crop plants, yet they cause serious losses in vegetables, pulses, fruit trees, plantation crops and ornamentals across India. Most of them cannot be seen clearly with the naked eye, so their damage is often mistaken for a virus, a nutrient deficiency or insect attack, and the crop ends up receiving the wrong spray. This article explains how mites differ from insects and describes the four groups of plant-feeding mites that matter most in Indian agriculture: spider mites, tarsonemid mites, eriophyid mites and flat mites. The typical symptoms of each group are described along with simple field checks, such as the white paper tap test and hand lens examination, and pointers for separating mite injury from look-alike problems. Correct recognition in the field is the first and most important step in managing mites.

**Keywords:** Acari, spider mite, broad mite, eriophyid mite, symptoms

## Introduction

Many plant samples that reach an acarology laboratory come with the same history. The leaves are curled, bronzed or dried, the farmer has already sprayed once for a virus and once for sucking insects, and the problem has only become worse. Under the microscope the cause turns out to be a mite, often so small that a hundred of them would fit on a grain of rice. By then the crop has lost several weeks and the grower has spent money on chemicals that never reached the real pest.

Mites belong to the subclass Acari of the class Arachnida, the same class that includes spiders, scorpions and ticks. More than 40,000 species of mites have been described (Grbić *et al*., 2011). Most of them live in soil, water or on animals, and only a small share feed on plants. That small share, however, includes some of the most difficult pests in agriculture. The two-spotted spider mite, *Tetranychus urticae* Koch, alone has been recorded on more than 1,100 plant species belonging to over 140 plant families (Grbić *et al*., 2011). Mites were once treated as secondary pests in India. Intensive cropping, protected cultivation, longer dry spells and the repeated use of broad-spectrum insecticides have since pushed several of them to the status of key pests.

## How a Mite Differs from an Insect

An adult mite has four pairs of legs, whereas an adult insect has three. The young larva that hatches from the mite egg has only three pairs, and the eriophyid mites keep just two pairs throughout life, so leg count alone can mislead. Mites have no antennae and no wings. Their body is not divided into head, thorax and abdomen; instead it has a small front part carrying the mouthparts (gnathosoma) and a large sac-like body (idiosoma). Plant-feeding mites use needle-like chelicerae to pierce plant cells and suck out their contents. Adults of most pest species measure between 0.1 and 0.5 mm, which means they appear as moving dots, if they are seen at all. These differences have a direct

practical meaning. Many insecticides commonly sprayed in the field have little or no effect on mites, and some of them make the mite problem worse by killing the natural enemies that keep mites in check. Knowing that the pest is a mite is therefore the starting point for choosing any control measure.

**Major Groups of Plant-Feeding Mites**

**Spider mites (Tetranychidae):** This is the largest and best-known group of mite pests. Adults are oval, about 0.4 to 0.5 mm long, and red, green, orange or yellowish depending on species and season. *T. urticae* usually shows two dark spots on its back. Colonies live mostly on the lower surface of leaves and many species spin fine silk webbing. Each mite empties the cells it feeds on, which shows on the upper surface as tiny white or yellow specks (stippling). As feeding continues the leaf turns pale, bronzed or ash-coloured, dries and falls. In heavy infestations webbing covers the leaves and growing tips, and mites can be seen moving along the threads. Common examples are *T. urticae* and *T. macfarlanei* Baker & Pritchard on okra, brinjal, beans and cucurbits, *Oligonychus indicus* (Hirst) on sorghum and sugarcane, *Oligonychus coffeae* (Nietner), the red spider mite of tea, and *Schizotetranychus* species that live under sheets of web on sugarcane leaves.

**Tarsonemid mites (Tarsonemidae):** These are tiny (about 0.2 mm), shiny, pale yellow to whitish mites that do not spin webs. They avoid light and stay in the growing tips, buds, flowers and the lower surface of young leaves. Their saliva is toxic, and a small number of mites can produce severe distortion. The broad mite or yellow mite, *Polyphagotarsonemus latus* (Banks), has been recorded on plants of more than 60 families (Gerson, 1992) and is a major pest of chilli, capsicum, jute, potato and tea in India. On chilli the leaves curl downwards, become narrow, thick, leathery and brittle, and the lower surface takes on a shiny bronze tinge. Flower buds drop and fruits develop corky brown scars. The rice sheath mite, *Steneotarsonemus spinki* Smiley, belongs to the same family. It feeds hidden inside the leaf sheath, leaving brown discoloured patches, and is linked with poorly filled grains.

**Eriophyid mites (Eriophyidae):** These are the smallest of all plant-feeding mites, only 0.1 to 0.3 mm long, worm- or cigar-shaped, with two pairs of legs near the front end. They cannot be seen without a lens of at least 20x magnification. Most species are restricted to one host or a few closely related plants. Their feeding changes the way plant tissue grows, which gives rise to galls, blisters, velvety felt-like hair patches called erineum, rusting or russeting of the surface, and malformed buds. The coconut mite, *Aceria guerreronis* Keifer, lives under the perianth of tender nuts. It was first reported in India from Ernakulam district of Kerala in 1998 (Sathiamma *et al*., 1998) and spread to other coconut-growing states. The first sign is a pale triangular patch just below the perianth. This later turns brown, warty and cracked, and the affected nuts remain small or drop early (Navia *et al*., 2013). The litchi erinose mite, *Aceria litchii* (Keifer), causes curling of leaves with a brown velvety growth on the lower surface. In pigeonpea, *Aceria cajani* Channabasavanna transmits the sterility mosaic virus. Infected plants turn bushy and pale green with a mosaic, and set few or no flowers. The disease has been estimated to cost Indian growers more than US $300 million every year (Patil and Kumar, 2015).

**Flat mites or false spider mites (Tenuipalpidae):** These are flat, slow-moving, red to orange mites about 0.3 mm long that do not produce webbing. They feed on the lower leaf surface, mainly along the veins, and on young stems, bark and fruit. Damage shows as bronzed or brown scabby patches and leaf fall. The scarlet mite, *Brevipalpus phoenicis* (Geijskes), attacks tea, citrus and papaya, and

the red palm mite, *Raoiella indica* Hirst, feeds on coconut and arecanut. Some *Brevipalpus* species transmit leprosis viruses of citrus in other countries (Childers and Rodrigues, 2011), which makes this group important for quarantine as well.

The main features of the four groups are compared in Table 1.

**Table 1. Field features of the four major groups of plant-feeding mites**

| Group | Size and appearance | Where to look | Typical symptom | Common examples |
|---|---|---|---|---|
| Spider mites (Tetranychidae) | 0.4-0.5 mm, oval, red, green or yellow; spins webbing | Lower surface of mature leaves | Fine white or yellow specks, bronzing, webbing, leaf drop | *T. urticae* on okra and brinjal; *O. indicus* on sorghum; *O. coffeae* on tea |
| Tarsonemid mites (Tarsonemidae) | About 0.2 mm, shiny, pale yellow or white; no webbing | Growing tips, buds, young leaves, leaf sheath | Downward curling, thick brittle leaves, bud drop, corky fruit | *P. latus* on chilli and jute; *S. spinki* on rice |
| Eriophyid mites (Eriophyidae) | 0.1-0.3 mm, worm-like, two pairs of legs | Buds, under perianth, inside galls or erineum | Galls, erineum, russeting, nut scarring, virus spread | *A. guerreronis* on coconut; *A. litchii* on litchi; *A. cajani* on pigeonpea |
| Flat mites (Tenuipalpidae) | About 0.3 mm, flat, red or orange, slow; no webbing | Along veins, stems, bark, fruit | Bronzed or brown scabby patches, leaf fall | *B. phoenicis* on tea and citrus; *R. indica* on coconut |

**Simple Field Checks to Confirm Mites**

**White paper tap test:** Hold a sheet of white paper or a white board under a branch or a few leaves and tap them sharply. Spider mites and flat mites fall on the paper as slowly moving dots. When crushed, spider mites leave a red or green smear. Thrips also fall, but they are long and move quickly.

**Hand lens:** A 10x lens is enough for spider mites and flat mites, along with their round eggs and white cast skins. Tarsonemid and eriophyid mites need 20x or more, and a laboratory microscope is often required for certain identification.

**Search at the right place:** Each group has its own hiding place. Look at the lower surface of middle and lower leaves for spider mites, the youngest leaves and buds for broad mite, under the perianth of tender nuts for coconut mite, and inside the leaf sheath for rice sheath mite. Spider mite attack usually starts in patches along dusty field borders and roads, and then spreads, so the field edge is a good place to begin.

**Sending samples:** Place affected leaves in a polythene bag with a piece of dry tissue paper, seal it, and send it to the nearest university or KVK laboratory within a day. Galls, erineum and coconut buttons should be sent as such, without washing.

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**Is It Mite Damage or Something Else?**

**Nutrient deficiency:** Deficiency yellowing usually follows a regular pattern, such as between the veins or along the margins, and appears on leaves of the same age throughout the field. Spider mite stippling is made of fine separate dots, begins in patches, and the mites, eggs or webbing can be found on the lower surface.

**Viral leaf curl:** Broad mite damage on chilli is often taken for leaf curl virus. Mite-affected leaves curl downwards and become thick and brittle with a shiny lower surface, and new growth recovers once the mites are controlled. Virus-affected plants usually show vein yellowing, mosaic or puckering, whiteflies are often present, and the plant does not recover after an acaricide spray.

**Thrips injury:** In chilli, thrips cause the leaves to curl upwards in a boat shape with silvery streaks, while mites cause downward curling. Both may be present together, which is the familiar leaf curl complex known to farmers as *murda*.

**Fungal growth and herbicide injury:** The erineum produced by eriophyids can look like a fungal felt, but under a lens it is made of plant hairs with mites moving between them. Drift of hormone-type weedicides such as 2,4-D also twists young leaves, so it is worth asking whether any weedicide was sprayed nearby.

**Why Mite Numbers Rise Suddenly**

Mite problems often appear suddenly because spider mites can complete a generation in about a week in hot weather. Outbreaks are most likely during hot, dry and dusty spells, in water-stressed crops, inside polyhouses, and in fields that have received repeated sprays of synthetic pyrethroids or other broad-spectrum insecticides, which remove the natural enemies of mites. Fields with these conditions should be checked more often.

**After Recognition**

Once the pest is confirmed as a mite, count the mites on a few leaves before deciding on a spray and treat the first patches early. Use an acaricide recommended for that crop rather than a general insecticide, and protect natural enemies, especially predatory mites, wherever possible.

**Conclusion**

Plant-feeding mites are small in size but large in their effect on Indian crops. Spider mites leave stippling and webbing, tarsonemid mites cause severe distortion of tender parts, eriophyid mites produce galls, erineum and scars and some transmit viruses, while flat mites cause bronzing and scabby patches. A 10x to 20x hand lens, a sheet of white paper and knowledge of where each group hides are enough to confirm most mite problems in the field. Farmers and extension workers who can recognise mite damage early avoid wasteful sprays and protect the natural enemies that hold mites in check. Wider training in mite recognition, regular field surveillance and diagnostic support from the AINP on Agricultural Acarology centres and agricultural universities will help bring mite problems under control before they turn into outbreaks.

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# CLIMATE STRESS AND THE MICROBIOME–IMMUNE–EPIGENOME AXIS IN FINFISH: MECHANISMS, CONSEQUENCES AND ADAPTIVE RESPONSES

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**Abstract**
Climate change is reshaping aquatic environments through rising water temperatures, deoxygenation, acidification and shifting salinity, exposing finfish to chronic and acute physiological stress. These stressors converge on an integrated network linking the gut microbiome, the immune system and the epigenome. Thermal stress alters intestinal microbiota diversity and composition, often reducing beneficial taxa and favouring opportunistic pathogens (dysbiosis). In parallel, temperatures outside the thermal optimum frequently suppress innate and adaptive immunity, while environmental cues reprogramme gene expression through epigenetic mechanisms such as DNA methylation. This article reviews the mechanistic links across this microbiome–immune–epigenome axis in finfish, their consequences for health and aquaculture, and adaptive responses including behavioural fever and transgenerational epigenetic inheritance—knowledge essential for predicting the resilience of wild stocks and designing climate-ready aquaculture.

**Keywords**
Climate stress; fish gut microbiome; teleost immunity; DNA methylation; dysbiosis; epigenetics; aquaculture; thermal tolerance.

## Introduction

Finfish are ectotherms whose physiology is tightly coupled to the temperature and chemistry of the surrounding water. As global warming raises mean and extreme water temperatures and intensifies hypoxia and acidification, fish increasingly experience conditions outside their physiological optima, at a biological cost extending well beyond simple metabolic strain. A growing body of evidence shows that climate-related stress acts simultaneously on three interdependent systems: the microorganisms colonising the gut and mucosal surfaces (the microbiome), the host defence network (the immune system), and the regulatory layer controlling gene expression without altering DNA sequence (the epigenome).

These systems are not independent: the gut microbiome protects the intestinal barrier, prevents overgrowth of opportunistic pathogens and shapes host immunity, while the immune system in turn regulates microbial composition, and epigenetic marks sit above both, translating environmental signals into durable changes in gene expression. This review frames climate stress through this integrated microbiome–immune–epigenome axis, outlining its mechanisms, consequences for fish health and aquaculture, and adaptive responses.

## Mechanisms Along the Axis

### Climate stress reshapes the microbiome

Fish gut microbiomes are dominated across most taxa by Proteobacteria, Fusobacteria and Firmicutes, with Actinobacteria common in many species; diversity tends to be highest in

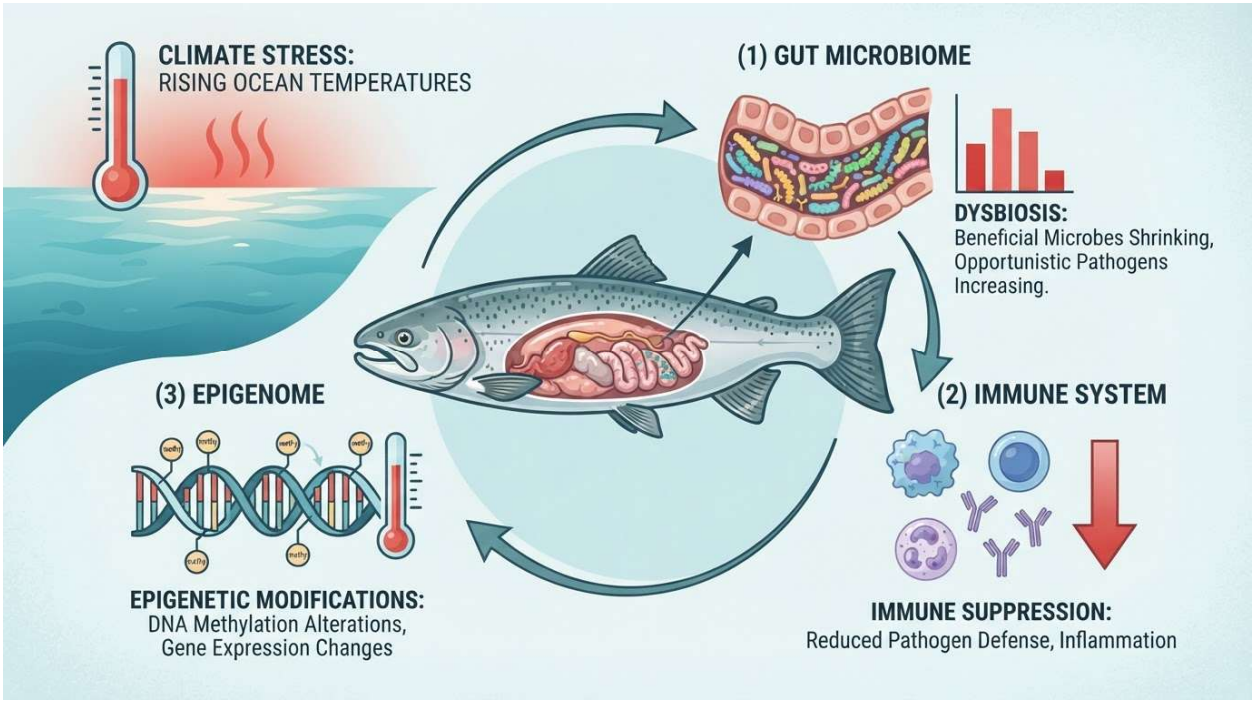
temperate, subtropical, and sub-equatorial regions (Kanika *et al*., 2025). Because these communities are sensitive to temperature, oxygen, pH and salinity, climate stress readily perturbs them. Systematic analysis of freshwater fish shows that thermal stress consistently alters microbiota diversity and composition, typically reducing overall diversity and depleting beneficial phyla such as Firmicutes and Actinobacteria (Dobre *et al*., 2026). Warming can also raise intestinal oxygen levels and favour opportunistic pathogens. The resulting imbalance—dysbiosis—weakens colonisation resistance and the mucosal barrier, creating an entry point for disease.

**Temperature as a master regulator of immunity**

Temperature is the dominant environmental driver of the teleost immune response. Within a species' thermal optimum, moderate warming can enhance certain immune activities, but temperatures outside that window frequently suppress both innate and adaptive defences (Scharsack *et al*., 2022; Franke *et al*., 2024). Acute thermal stress disrupts energy metabolism and diverts resources away from immune function, increasing susceptibility to infection and, in severe cases, causing mortality (Ma *et al*., 2025). Because immunity and the microbiome are mutually regulating, immune suppression further loosens control over microbial communities, reinforcing dysbiosis in a self-amplifying loop.

**The epigenome translates stress into gene regulation**

Environmental stressors are encoded into gene regulation through epigenetic mechanisms, of which DNA methylation is the best characterised in fish; these marks facilitate immune responses during stress exposure (Franke *et al*., 2024). Experimental warming of even 2°C during sensitive larval stages significantly changed global DNA methylation and the expression of ecologically relevant genes in European sea bass (Anastasiadi *et al*., 2017). In Atlantic salmon, thermal and hypoxic challenges reshape stress- and immune-related transcriptional programmes (Beemelmanns *et al*., 2021), illustrating how the epigenome links external climate signals to the microbiome–immune interface.



**Consequences for Health and Aquaculture**

The combined disruption of these systems has concrete consequences. Dysbiosis and immune suppression together compromise the barriers that normally exclude pathogens, so warming events are frequently followed by disease outbreaks in wild and farmed populations. In intensive aquaculture, where high stocking densities already elevate baseline stress, thermal extremes can trigger rapid proliferation of opportunistic bacteria, reduced growth and increased mortality. Epigenetic reprogramming adds a longer time dimension, as methylation changes acquired under stress can persist and influence immune competence and growth after the stressor has passed. Because the three systems reinforce one another, a single stressor can produce effects larger and more persistent than any one pathway would predict.

**Adaptive Responses**

Finfish are not passive in the face of climate stress. Many species exploit thermal gradients to seek preferred temperatures; in salmonids, this behavioural fever has been linked to epigenetic modulation of the immune response, letting fish tune defence gene expression by selecting a warmer microhabitat (Boltana *et al*., 2018). The plasticity of the epigenome allows rapid, reversible adjustment of gene expression—far faster than genetic adaptation. Some temperature-induced epigenetic marks acquired by parents can even be transmitted to offspring never themselves exposed, a transgenerational plasticity that may pre-condition the next generation. The microbiome adds its own flexibility, often reassembling into functionally similar configurations once a stressor is relieved. These mechanisms also suggest interventions: probiotics, prebiotics and functional feeds, controlled early-life immune stimulation, and selective breeding for favourable epigenetic and immune profiles all offer routes to more climate-resilient aquaculture stock.

**Conclusion**

Climate stress in finfish is best understood not as a series of separate insults but as a coordinated disturbance of an integrated microbiome–immune–epigenome axis, in which rising and fluctuating temperatures reshape the gut microbiota, modulate immune competence and reprogramme gene expression, with each layer reinforcing the others. The consequences—dysbiosis, immune suppression, heightened disease risk and persistent, sometimes heritable, regulatory change—carry significant implications for the conservation of wild stocks and the sustainability of aquaculture. Yet the same axis also offers adaptive capacity. Integrating microbiome, immunological and epigenomic data within a single framework will be essential to predict which populations can cope and to engineer feeds, husbandry and breeding strategies that strengthen finfish resilience in a warming world.

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# CORAL REEFS: ECOLOGICAL IMPORTANCE, THREATS AND CONSERVATION STRATEGIES

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**Abstract**

Coral reefs, often referred to as the "tropical rainforests of the sea," are among the most diverse and productive marine ecosystems. They provide habitat and shelter for a wide variety of marine organisms, protect coastlines from erosion, support fisheries and tourism, and contribute to medical research and carbon cycling. Their distribution and development are influenced by environmental factors such as temperature, depth, light, salinity, sedimentation, wave action, and nutrient availability. However, coral reefs face significant threats from destructive fishing practices, overfishing, pollution, coral mining, diseases, careless tourism, and climate change. These pressures contribute to coral bleaching, habitat degradation, and biodiversity loss. Effective conservation requires an integrated approach involving public awareness, community-based management, marine protected areas, coral reef restoration, long-term monitoring, and strict enforcement of environmental regulations. Sustainable management and collaborative conservation efforts are essential to preserving coral reef ecosystems and ensuring their ecological and economic benefits for future generations.

## Introduction

Coral reefs are often referred to as 'tropical rainforests of the sea' since they are one of the most diverse, productive and beautiful marine ecosystems in the world. Coral reefs are formed by colonies of tiny marine animals called coral polyps, which secrete calcium carbonate skeletons over time. They are predominantly found in warm, shallow, clear marine waters where sunlight supports the growth of symbiotic algae called zooxanthellae. Despite covering a small portion of the ocean floor, coral reefs support nearly one-quarter of all marine species, making their conservation essential for maintaining marine biodiversity and ecological balance.

## Factors limiting the distribution of coral reefs

Coral reefs are sensitive to even for a slight change in the environment. Wide varieties of environmental factors are known to influence the distribution of coral reefs. There are six major physical factors that limit coral reef development and distribution viz., temperature, depth, light, salinity, sedimentation, exposure to air etc.

## Temperature

Reef building corals tend to live in shallow waters that border islands or continental shelves within the latitudes of 32° 30 N to 32° S, where waters are warmer. They grow in warm waters that range in temperatures from 18 – 36° C. The ideal temperature range for these corals is 25 – 29° C. Reef development does not occur in waters where the annual mean minimum temperature drop below 18° C. Optimal reef development occurs in waters where the mean annual temperatures are about 23-25° C.

**Depth**

Coral reefs are also limited by depth. They do not develop in water that is deeper than about 50-70m. Most reefs grow in depths of 25 m or less. This is evidenced by the fact that these structures are restricted to the margin of continents or islands. The reasons for the depth restriction have to do with the light requirement of zooxanthellae living together with hermatypic corals.

**Light**

Light is one of the most important factors limiting coral reefs. Reef building corals contain symbiotic algae (zooxanthellae) in its tissue and for these algae sufficient light must be available for carrying out photosynthesis. Without sufficient light these algae cannot survive and this leads to the death of the corals. Even if the water is shallow and warm, coral cannot survive if those waters are loaded with sediments as this blocks critical sunlight from penetrating far below the surface.

**Salinity**

If is an important factor that restricts coral reef development. Hermatypic corals are true marine organisms and are intolerant of salinities deviating significantly from that of normal seawater (32-35 ppt). Wherever inshore waters are subject to continuing influxes of freshwater from river discharge so that the salinity is lowered reef will be absent. Coral reefs do occur in regions of elevated salinity such as the Persian Gulf where reefs flourish at 42 ppt.

**Sedimentation**

Sedimentation in the marine is a process caused due to the freshwater runoff from the adjoining land mass. Sediment suspended in the water settle out on the coral reefs has an adverse effect on the corals. Many corals can remove limited amounts of sediment by trapping it in mucus and carrying it off by ciliary action. Most hermatypic corals, however cannot withstand heavy sedimentation which overpowers their ciliary-mucus cleansing mechanism clogs their feeding structures and smothers them. Sediment in the water also reduces the light necessary for photosynthesis by the zooxanthellae in the coral tissue. As a result, coral reef development is reduced or eliminated in areas of high turbidity. When this sediment is carried by rivers or streams the combination of reduced salinity and excess sediment is also responsible for the absence of reefs.

**Wave action**

Coral colonies with their dense, massive skeletons of calcium carbonate are very resistant to damage by wave action. At the same time, the wave action provides a constant source of fresh, oxygenated seawater and prevents sediment from settling on the colony. Wave action is also responsible for renewing the plankton, which is food for the coral colony.

**Exposure of air**

Finally, coral reefs are limited in an upward direction by emergence into air. Though abundant secretion of mucus may prevent dehydration for a short time by exposure to air for an hour or two most corals are killed by such long exposure.

**Nutrient loading and contaminant inputs**

The symbiotic relationship between reef building corals and zooxanthellae allows them to thrive in the nutrient poor “marinedeserts” of the tropical oceans. Addition of nutrients to the water may harm corals directly (if concentrations are sufficiently high) or make the environment less favourable for reefs by promoting growth of phytoplankton (which reduces water clarity and light availability) and of seaweeds (macroalgae) that compete with corals for space on the reef. Additional organic

production resulting from nutrient loading can also increase populations of bioreactors that break down coral skeleton and reef structures. Unlike nutrients, contaminants are generally human produced toxic materials which include heavy metals, pesticides and herbicides, solvents, fuels and other compounds. These materials may be part of complex waste streams discharged to the ocean or absorbed in sediment.

**Animals associated with coral reefs**

Coral reefs provide habitats for a large variety of organisms. These organisms rely on corals as a source of food and shelter. Some organisms that use corals through mutualism, commensalism and parasitism are within the taxonomic groups Porifera, Polychaeta, Mollusca, Crustacea, Echinodermata and Pisces (butterfly fishes – Chaetodontidae, pufferfishes – Tetraodontidae, parrotfishes – Scaridae etc).

Sponges (Porifera) are found inhabiting cavities in the reef. They remove small chips of calcium carbonate from corals. These sponges such as *Cliona* cause bioerosion in corals. Sponges inhabit corals for the purpose of protection from predators. Polychaetes such as *Hermodice carunculata* and gastropods in the family Trochidae depend on corals for food. The giant clam, *Tridacna* sp commonly occur in coral reef areas. They feed on corals such as *Porites* and *Agaricia*. Decapod crustaceans such as shrimps and crabs depend on corals for shelter. Xantid crabs form cavities in the coral *Acropora palmata*. Fish also depend on corals for protection against predators.

Echinoderm such as *Acanthaster planci* (star fish commonly called as crown of thorns) are coral's top most predator which feeds exclusively on coral polyp and devastate the entire reef areas id swarming of this predatory star fish occurs. There are many other species of fungi, sponges, sea worms, crustaceans and molluscs that bore into coral skeletons. Other organisms that inhabit the coral reefs include variety of fin fishes, sea urchins, jelly fishes, oysters, clams, turtles and sea anemones.

**Importance of corals**

- Corals are the basis for the formation of other ecosystems; through the action of currents, leads to the formation of islands and shallows, and ultimately to the formation of mangroves and other coastal forests
- Important for protection of coastal ecosystem: Reefs are found along more than 150,000 km of coastline in more than 100 countries and territories.
- They form a barrier that absorbs the forces of waves, currents, storms, hurricanes, etc. coming from the open sea, thereby reducing coastal erosion.
- Thus, they protect both the ecosystems between the reefs and the coasts, such as lagoons with seagrass beds, as well as human settlements along the coast.
- An important source of Food resource: Reef animals are an important source of protein. Coral reefs provide about 10% of the fish caught worldwide (70-90% for the Southeast Asian countries)
- Important for carbon sequestration: Coral reefs (made of calcium carbonate) are an important reservoir of carbon and help sequester ocean carbon, thus are an important part of the carbon cycle.
- Importance for Medicine: Coral organisms are used in the search for treatments for certain cancers or the aging of cells. The coral's skeleton, (used since 1970) for bone grafts, is a promising lead for bone regeneration.

- Economic importance: As per an estimate, the total annual net benefit of the world's coral reefs is $29.8 billion. Reefs are the backbone of tropical regions' economies, through reef-related tourism and marine exports.

**Threats to coral reefs**

Roughly one quarter of coral reefs worldwide are already considered damaged beyond repair with another two thirds under serious threat. Major threats to coral reefs and their habitats include:

1. **Destructive fishing practices**: These include cyanide fishing, blast or dynamite fishing, bottom trawling and banging on the reef with sticks. Bottom trawling is one of the greatest threats to cold-water coral reefs.
2. **Overfishing:**This affects the ecological balance of coral reef communities, warping the food chain and causing effects far beyond the directly overfished population.
3. **Careless tourism:**Careless boating, diving, snorkelling and fishing happens around the world with people touching reeds, stirring up sediment, collecting coral and dropping anchors on reefs. Some tourist resorts and infrastructure have been built directly on top reefs and some resorts empty their sewage or other wastes directly into water surrounding coral reefs.
4. **Pollution:**Urban and industrial waste, sewage, agrochemicals and oil pollution are poisoning reefs. These toxins are dumped directly into the ocean or carried by river systems from sources upstream. Some pollutants such as sewage and run off from farming, increase the level of nitrogen in seawater causing an overgrowth of algae which "smothers" reefs by cutting off their sunlight.
5. **Sedimentation:**Erosion caused by construction (both along coasts and inland), mining, logging and farming is leading to increased sediment in rivers. This ends up in the ocean where it can "smother" corals by depriving them of the light needed to survive. The destruction of mangrove forests which normally trap large amounts of sediment is exacerbating the problem.
6. **Coral mining:**Live coral is removed from reefs for use as bricks, road-fill or cement for new buildings. Corals are also sold as souvenirs to tourists and to exporters who don't know or don't care about care about the longer-term damage done and harvested for the live rock trade.
7. **Climate change**: Corals cannot survive if the water temperature is too high. Global warming has already led to increased levels of coral bleaching and this is predicted to increase in frequency and severity in the coming decades. So, worldwide integrated approach to prevent global warming is immediate need for the protection of coral reefs.
8. **Coral diseases**: The common diseases that noticed in Indian Ocean are White band disease which is caused by*Rickettsia* bacteria, *Vibrio charchari.* Black band disease where the black band appears with thickness 0.5-1 cm and it is caused bycyanobacteria, fungus, sulfate reducing bacteria and sulfide oxidizing bacteria. Pink spot disease - the pink band of 3-10 mm and it is caused by fungi and cyanobacteria.

**Conservation and management measures**

The world has woken up to the magnitude of the problem and has taken steps to halt the degradation of one of the richest ecosystems. The convention on International Trade in Endangered Species of Wild Fauna and Flora or CITES has classified many corals as threated species. The establishment of marine sanctuaries or reserves may help ensure the protection of this ecosystem

in the years to come. In addition, more focused actions should be taken to protect, conserve and manage these valuable resources. The following are the measures to be under taken on an integrated basis:

- Creation of awareness and environmental education
- Need to provide alternative/additional livelihood options
- Community based reef ecosystem protection and management
- Coral reef restoration and re-habitation
- Enforcement mechanism
- Baseline data
- Need for long term reef monitoring
- Sea ranching for enhancement of stock
- Marine biodiversity data management

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# FIGHTING "HIDDEN HUNGER" VIA BIOFORTIFICATION

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**Abstract**
Hidden hunger affects over 2 billion people worldwide particularly in developing nations where diverse nutrient-rich diets remain inaccessible. Micronutrient deficiencies continue to compromise immune function and overall health across vulnerable populations. Biofortification has emerged as a sustainable, cost-effective strategy to combat this challenge by enhancing the bioavailable micronutrient content of staple food crops. Three major approaches of biofortification are discussed in this article. Agronomic biofortification, which employs soil and foliar fertilizer applications along with beneficial microorganisms to boost nutrient uptake; conventional breeding, which selects and crosses plants for naturally higher micronutrient traits, often accelerated through marker-assisted selection; and transgenic/biotechnological methods, which utilize gene introduction and genome-editing tools such as CRISPR/Cas9 to precisely enhance nutrient biosynthesis. Despite notable progress, challenges including low consumer awareness, limited variety availability, distribution constraints, and regulatory hurdles persist. Integrating multi-nutrient biofortification with emerging nanotechnology offers a promising path toward more comprehensive, holistic solutions to global malnutrition.

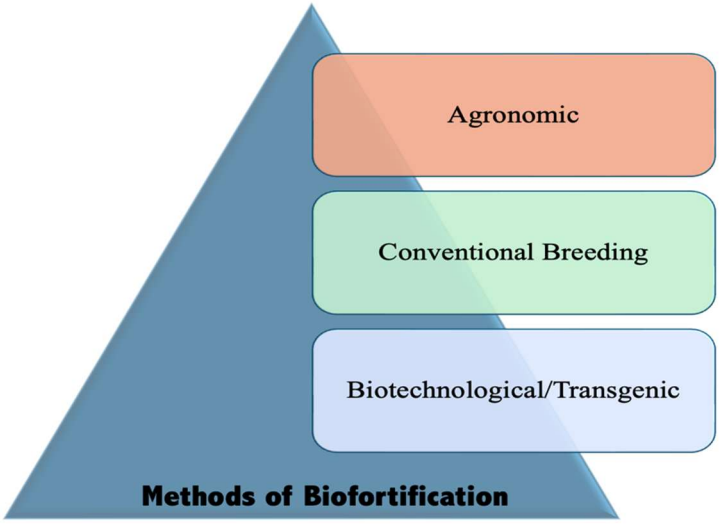
**Keywords**: Biofortification, Micronutrients, Approaches

## Introduction

Hidden hunger usually refers to a condition that occurs when the body lacks essential vitamins and minerals that are required in small amounts for proper growth, development and overall health. Over 2 billion people around the world suffer from micronutrient deficiency which has a negative impact on their health and socio-economic condition (Sheoran *et al.,* 2022). These deficiencies are particularly common in developing countries, where a lack of access to a varied and nutritious diet makes it difficult for people to get the micronutrients they need. Micronutrient has a potential role in supporting immune function and overall health. Iron (Fe), zinc (Zn), iodine (I), and selenium (Se) deficiency in humans are significant food-related issues worldwide (Gomati *et al.,* 2017). Biofortification is the process of increasing the bioavailable concentration of essential micronutrition elements in the edible portions of crop plants through selective breeding of crops to have higher levels of specific nutrients, agronomic approach using fertilizers and other inputs to increase nutrient uptake by crops and transgenic approach, which could be a way to hidden hunger mitigation. Biofortification also a sustainable, cost effective and long term means to address micronutrient deficiencies by increasing the levels of essential vitamins and minerals in staple crops that are widely consumed by people in affected communities.

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**Approaches of biofortification for improvement of nutritional profile**




**Agronomic Approaches**

Agronomic approaches aims to increase the uptake and translocation of minerals from the soil to edible plant parts by applying fertilizers in soil, foliar application of fertilizers and inoculation of soil with beneficial microorganisms. Fertilizers containing micronutrients viz zinc, selenium, iodine, and iron are commonly used for biofortification. The application of micronutrients through fertilizers can improves the concentration of these nutrients in grains and edible tissues. Micronutrients containing fertilizers are sprayed directly onto plant leaves, resulting in better nutrient uptake than soil application in many crops. Leaves absorb nutrients rapidly and provides better nutrient-use efficiency than soil application because it bypasses problems associated with nutrient fixation in the soil. Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi improve nutrient uptake by solubilizing nutrients in soil and also improve soil health.

**Table 1: Nutrient Enrichment in different crops through agronomic approaches**

| Crop | Targeted Nutreient | Treatment | Reference |
|---|---|---|---|
| Maize | Zinc | Soil application of $ZnSO_4.7H_2O$ @ 2.5, 5 and 7.5 kg/ha | Faujdar *et al*., 2014 |
| Potato | Iodine | KIO3 @ 2.0 kg iodine per hectare | Smolen *et al.,* 2020 |
| Chickpea | Selanium | Two foliar Se fertilizers) at four different rates (0, 10, 20, 40 g $ha^{-1}$) | Poblaciones *et al*., 2014 |
| Rice | Iron | Foliar application of $FeSO_4$ sprayed | Tilocca *et al*., 2014 |

**Conventional Breeding Approaches**

Conventional plant breeding is a method of improving the nutritional content of crops by selecting for desired traits through effective breeding. The process involves selecting plants with desirable traits such as higher micronutrient content and crossing them with other plants to create a hybrid with improved characteristics and further go for multi-location evaluation for yield stability and nutrient consistency. Those evaluated biofortified varieties released for cultivation. Biofortification

by breeding is attained when crops have naturally some concentrations of micronutrients, such as iron, zinc and vitamin A, which means when genetic diversity is accessible in usable form. This method is widely accepted as it is safe and does not raise the same safety concerns as genetic engineering. However, traditional breeding can be a slow and labour intensive process, and it may take many years to develop a crop with improved nutrient content. Modern breeding programmes also use marker-assisted selection (MAS) to accelerate the identification of plants carrying desirable genes.

**Table 2: Varieties developed through conventional breeding**

| Crop | Variety | Trait | Reference |
|---|---|---|---|
| Rice | DRR Dhan 45, DRR Dhan 48, Saurabhi | Zn | Rao *et al*., 2020 |
| | CR 310, CR 311 | Protein | Korram *et al*., 2022 |
| Wheat | HD 3171 | Zn | Yadava *et al*., 2019 |
| Maize | Vivek QPM 9, Pusa HM8 improved, Pusa HM4 | Lysine and tryptophan | Yadava *et al*., 2019 |
| Pearl millet | RHB 233, RHB 234 | Iron and Zinc | Yadava *et al*., 2019 |
| Cowpea | Pant Lobia-7 | Iron | Yadava *et al*., 2019 |

**Transgenic/Biotechnological Approaches**

Biotechnology has the potential to deal with a number of the world's severe problems such as the restriction of food supply, the creation of new treatments for existing diseases, and the improvement of the nutritional value of crops. The nutritional value of crops can be increased by introducing new genes which enable the plants to contain more vitamins or minerals or by improving the expression of genes that are already present and which play a role in the biosynthesis of nutrients. Modern biotechnology introduces or alters the genes responsible for nutrient accumulation using transgenic technology and genome editing (CRISPR/Cas9, TALENs, ZFNs) in order to make precise changes to the genes involved in nutrient production.

**Table 3: Genes involved in nutritional enrichment**

| Crop | Genes | Micronutrients | Reference |
|---|---|---|---|
| Wheat | NAM B1, GPC 1 and Phy A | Zn and Fe | Malik *et al*., 2016 |
| Rice | OsVIT1, OsVIT2 | Fe | Inoue *et al*., 2003 |
| Maize | crtI, crtB | Vitamin A | Faujdar *et al.,* 2014 |
| Linseed | PSY, crtB | Caroteniods | Fujisawa *et al*., 2008 |
| Potato | nptII | Amylopectin | Tilocca *et al.*, 2014 |

**Challenges**

- Peoples may not be aware of the benefits of biofortified crops or may have misconception about their safety or nutritional value.
- Limited availability of biofortified varieties in the market and for cultivation.
- Limited distribution and access of biofortified varieties.
- Biofortification programs require funding for research, development, and implementation support.
- The development and commercialization of genetically modified (GM) crops, which are a potential tool for biofortification, can be subject to complex and often controversial regulations.

**Conclusion**

Biofortification is a powerful tool for fighting malnutrition and hidden hunger, which often go unnoticed. High-yielding biofortified crops can improve food security and boost farmers' incomes. Combining multi-nutrient biofortification with advanced nanotechnology represents a major step forward. Still, several challenges must be addressed to make biofortification programs successful. These include limited availability of biofortified crops, high production costs, low awareness, restricted distribution, and political or regulatory obstacles. Multi-nutrient biofortification or combinatorial biofortification is a new approach of biofortifying crops with multiple essential micronutrients to improve overall human nutrition. This strategy can provide a more holistic and comprehensive approach to combating malnutrition by addressing multiple nutrient deficiencies concurrently.

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# e-EXTENSION IN FISHERIES: TAKING SCIENTIFIC ADVICE TO THE LAST MILE

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**Abstract**
Fisheries and aquaculture play a vital role in India's food security, livelihoods and economic growth. However, the effective transfer of scientific knowledge to fish farmers and fishers remains a persistent challenge. Traditional extension methods, while important, often face limitations in reach, speed and personalization. In this context, digital advisory services, commonly referred to as e-extension, have emerged as a significant complement to conventional approaches. This article examines the concept of e-extension in fisheries, reviews major digital platforms and initiatives in India including the National Fisheries Digital Platform, Matsya Setu, Aqua One Centers, Matsya Varta, INCOIS Potential Fishing Zone advisories and Kisan Sarathi and analyses their benefits and constraints. Evidence indicates that digital tools enhance the timeliness, accessibility, and relevance of scientific advice, contributing to improved decision-making and productivity. Nevertheless, challenges related to digital literacy, connectivity, content localization, and institutional integration persist. The article emphasizes the need for hybrid extension models, capacity building of stakeholders, farmer-centric design, and stronger research extension linkages. For students and academicians in Fisheries Extension, the domain offers substantial scope for research, innovation and field application towards building a more knowledge-driven and resilient fisheries sector.

**Keywords:** e-extension, Digital Advisory, Fisheries Extension, Aquaculture, ICT

## Introduction

Fisheries and aquaculture contribute significantly to India's food security, livelihoods and export earnings. Yet the sector continues to face a persistent challenge: the timely transfer of scientific knowledge from research institutions to fish farmers and fishers. Traditional extension approaches, though valuable, often struggle with reach, speed and personalization. In this context, digital advisory services commonly termed e-extension have emerged as a powerful complement to conventional systems. By leveraging mobile technology, web platforms and interactive tools, e-extension is reshaping how scientific advice reaches the last mile in fisheries (Department of Fisheries, 2024; Lahiri *et al*., 2025). This article examines the concept, major initiatives, benefits, challenges and future directions of digital advisory services in Indian fisheries, with particular relevance for students and academicians in Fisheries Extension.

## Understanding e-Extension in Fisheries

e-Extension refers to the use of Information and Communication Technologies (ICTs) to deliver timely, location-specific and demand-driven advisory services. In fisheries, it encompasses mobile applications, SMS/IVRS systems, web portals, WhatsApp-based groups, interactive voice response platforms and emerging AI-enabled decision-support tools. Unlike one-way mass media approaches, modern e-extension emphasises two-way communication, allowing farmers to raise

queries and receive expert responses. It also supports continuous capacity building through digital learning modules, videos and real-time alerts on weather, disease, water quality and market information (Lahiri *et al*., 2025; ICAR, 2021).

**Major Digital Platforms and Initiatives in India**

Several government and institutional initiatives have strengthened the digital advisory ecosystem in Indian fisheries. The National Fisheries Digital Platform (NFDP), launched by the Department of Fisheries, provides a unified digital identity for fishers and fish farmers while facilitating access to schemes, credit, insurance, training and extension services (Department of Fisheries, n.d.). The Matsya Setu app, developed by ICAR-Central Institute of Freshwater Aquaculture with support from the National Fisheries Development Board, offers species-wise and subject-wise self-learning modules on breeding, seed production, grow-out culture and better management practices, along with query-based expert advisories (Ministry of Fisheries, Animal Husbandry and Dairying, 2021; ICAR-CIFA, n.d.). Under the Pradhan Mantri Matsya Sampada Yojana, Aqua One Centres function as ICT-enabled hubs providing water quality testing, disease diagnosis, better management practices and digital advisory support to registered farmers (National Fisheries Development Board, 2025). Matsya Varta, a farmer-centric mobile agro-advisory system implemented by the College of Fisheries, Central Agricultural University, Tripura, delivered need-based information on pond management, fish health, weather and schemes to smallholder farmers in the North-East between 2019 and 2023 (Lahiri *et al*., 2025). The Indian National Centre for Ocean Information Services issues Potential Fishing Zone advisories based on satellite data, disseminated through SMS, apps and other channels, which have been shown to reduce search time and improve catch efficiency among marine fishers (INCOIS, n.d.). Complementing these, Kisan Sarathi, an integrated platform of ICAR and MeitY, connects farmers with scientists from Krishi Vigyan Kendras and research institutes for multi-channel advisories, including fisheries-related content (ICAR, 2021). Together, these platforms, along with specialised apps and moderated social media groups, form a growing digital ecosystem for knowledge dissemination in the sector.

**Benefits of Digital Advisory Services**

Digital advisory services offer several clear advantages in fisheries extension. They enable the rapid delivery of time-sensitive information on disease outbreaks, extreme weather and market prices, thereby overcoming geographical barriers and reaching farmers in remote areas more effectively than conventional methods. These tools are cost-effective, expanding coverage while reducing the need for frequent physical visits by extension personnel. Location-based and query-driven platforms allow greater personalisation of advice, addressing the specific needs of individual farmers rather than relying on generic recommendations (Lahiri *et al*., 2025).

Continuous access to learning materials through apps and digital modules supports ongoing capacity building and better knowledge retention. Access to scientific guidance on feeding regimes, water quality management and stocking densities helps farmers make more informed decisions, which can lead to higher productivity and reduced production risks. In addition, digital platforms facilitate systematic documentation of farmer queries and feedback, enabling continuous improvement of advisory content. Evidence from marine fisheries shows that Potential Fishing Zone advisories have contributed to reduced search time, higher catch rates and fuel savings, while inland aquaculture initiatives have helped smallholders adopt better management practices and respond more effectively to disease challenges (INCOIS, n.d.; Lahiri *et al*., 2025).

**Challenges in Adoption and Effectiveness**

Despite the progress made, several constraints continue to limit the full potential of e-extension in fisheries. Digital literacy and smartphone access remain uneven, particularly among older farmers, women and those living in remote rural and coastal areas. Language barriers and inadequate content localisation often reduce the relevance and usability of digital advisories across India's diverse agro-ecological and linguistic regions. Unreliable internet connectivity and limited electricity supply further hinder consistent access in many locations. Ensuring sustained two-way interaction and maintaining the scientific credibility of information shared on informal platforms, such as unmoderated WhatsApp groups, requires stronger institutional oversight. Fragmented integration among different digital platforms frequently results in a disjointed user experience. Moreover, technology cannot fully replace the human dimensions of extension, including trust-building, hands-on demonstration and motivational support, which remain essential for effective technology adoption (Lahiri *et al*., 2025).

**Way Forward**

To strengthen e-extension in fisheries, a multi-pronged and integrated approach is essential. Hybrid extension models that combine digital tools with face-to-face methods through Krishi Vigyan Kendras, Matsya Seva Kendras and Aqua One Centres can enhance both reach and effectiveness. Systematic capacity building of extension functionaries and students in content development, digital facilitation and data interpretation is necessary to improve service quality. Platforms should be designed in a farmer-centric manner by involving end-users in testing and refinement to ensure greater usability and relevance. Expanding multilingual and multimedia content, including offline functionality, will help overcome connectivity and literacy barriers. Greater data integration and analytics linking platforms such as the National Fisheries Digital Platform with research databases and real-time monitoring systems can enable more precise and location-specific advisories. Academicians and postgraduate students have an important role in evaluating impact, identifying adoption barriers and developing context-specific digital extension models. Finally, carefully structured public–private partnerships with agri-tech startups and telecom providers can expand reach and innovation while safeguarding data privacy and maintaining the scientific quality of advisories.

**Conclusion**

e-Extension represents a significant evolution in fisheries advisory services. By taking scientific advice closer to the last mile, digital platforms are helping bridge long-standing knowledge gaps. However, technology alone is not sufficient. Its success depends on thoughtful integration with institutional extension systems, continuous capacity building, and a strong focus on inclusivity. For students and academicians in Fisheries Extension, this domain offers rich opportunities for research, innovation and field application. Strengthening digital advisory services in a farmer-centric and scientifically robust manner will be crucial for building a more productive, resilient and knowledge-driven fisheries sector in India.

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# ESTABLISHMENT OF A MUSHROOM SPAWN LABORATORY: EQUIPMENT, PRINCIPLES AND WORKING

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**Abstract**
Mushroom spawn is the vegetative inoculum used for the cultivation of edible and medicinal mushrooms. High quality spawn production requires pure cultures, effective sterilization and aseptic conditions. Establishment of a spawn laboratory requires proper layout, workflow and suitable equipments. This article describes the principles, major equipments and working requirements for establishing a mushroom spawn laboratory. Key equipment includes autoclave, hot-air oven, laminar airflow cabinet, incubator, refrigerator, pH meter and weighing balance. Their applications in sterilization, culture maintenance, inoculation and incubation are discussed. Proper laboratory organization and aseptic workflow are essential for minimizing contamination and ensuring consistent spawn production.

**Keywords:** Mushroom spawn, pure culture, spawn laboratory, equipment, sterilization, aseptic conditions.

## Introduction

Mushrooms are important cultivated fungi because of their nutritional, functional value and relatively short production cycle. Successful mushroom cultivation depends on several factors, among which the production of high-quality spawn is particularly important because spawn serves as the vegetative inoculum for mushroom cultivation. Spawn production involves a series of operations, including selection and maintenance of pure cultures, preparation of the spawn substrate, sterilization, cooling, aseptic inoculation and incubation. Each stage requires appropriate laboratory facilities and equipment to maintain sterile conditions and minimize contamination. The principal equipment includes an autoclave, laminar airflow cabinet, hot-air oven, BOD incubator, refrigerator, induction hot plate and weighing balance. Proper selection, arrangement and operation of these facilities are essential for efficient and consistent spawn production.

## Major Equipment Used in a Mushroom Spawn Laboratory

A mushroom spawn laboratory requires equipment for substrate preparation, media preparation, sterilization, aseptic inoculation, incubation and culture storage. The major equipment and their basic principles and functions are described below.

**Boiling vessels:** Boiling vessels are used for cooking or boiling cereal grains used as spawn substrates. Proper hydration and cooking provide the grains with a suitable texture for subsequent sterilization and inoculation.

**Electric heater/induction hot plate:** An electric heater or induction hot plate is used for boiling grains and heating or preparing culture media such as Potato Dextrose Agar (PDA). Grain cooking supports suitable texture and moisture adjustment but does not replace sterilization (Sharma and Kumar, 2011).

**pH meter:** A pH meter is used to measure the pH of culture media and other preparations. The pH can be adjusted to the desired level before sterilization to provide suitable conditions for fungal growth.

**Autoclave:**

**Principle and working:**

An autoclave operates on the principle of moist-heat sterilization using saturated steam under pressure. Increasing the pressure allows steam to reach temperatures above the normal boiling point of water. When steam contacts a cooler load, it condenses and releases heat, facilitating the transfer of thermal energy into the material. This process damages essential microbial structures and proteins, leading to the inactivation of microorganisms, including resistant bacterial spores, when the appropriate conditions are achieved (Centers for Disease Control and Prevention [CDC], 2023).

A commonly used reference condition is approximately 121°C at 15 psi gauge pressure. However, effective sterilization depends not only on temperature and pressure but also on exposure time, air removal, steam penetration, load size and the type of material being processed. The chamber should not be opened until the pressure has returned to a safe level**.** (Sharma and Kumar, 2011; CDC, 2023).

**Hot-air oven:**

**Principle and working:**

A hot-air oven sterilizes suitable materials by exposing them to dry heat. Heat is transferred from the heated air to the surface of the material and gradually penetrates it. Dry heat primarily inactivates microorganisms through oxidative damage and other heat-induced changes in essential cellular components. Because dry heat generally penetrates materials more slowly than saturated steam, it requires a suitable combination of temperature and exposure time (CDC, 2023). In a mushroom spawn laboratory, the oven is mainly used for suitable heat-resistant glassware and metal instruments. Items should be clean and dry before loading, and their arrangement should permit adequate circulation of hot air. The oven should not be overloaded, and materials should be allowed to cool sufficiently before handling. Dry heat is not a substitute for an appropriate moist-heat sterilization cycle for hydrated grain spawn (CDC, 2023).

**Laminar airflow cabinet:**

**Principle and working:**

A laminar airflow cabinet provides a clean working area by passing air through a High-Efficiency Particulate Air (HEPA) filter 0.3 micron in size. The filtered air moves across the work surface in a controlled, predominantly unidirectional stream, reducing the entry and accumulation of airborne particles that may contaminate exposed cultures or sterile materials. The cabinet is therefore useful for aseptic operations in mushroom culture and spawn preparation (Sharma and Kumar, 2011; University of New Hampshire, n.d.). Culture transfers and inoculation should be performed using appropriate aseptic techniques.

**BOD incubator:**

**Principle & Working:**

A Biochemical Oxygen Demand (BOD) incubator is a temperature-controlled chamber used to maintain biological samples under stable conditions. Its operation is based on feedback temperature regulation: a sensor measures the chamber temperature, and a controller regulates the heating and cooling systems to maintain the selected setting. (Khandpur, 2020).

In a mushroom spawn laboratory, a BOD incubator can be used to maintain fungal cultures and incubate spawn containers when its capacity and operating range are suitable for the intended purpose. The temperature should be selected according to the mushroom species, strain and stage of growth rather than applying one setting to all mushrooms. (Sharma and Kumar, 2011; Khandpur, 2020).

**Refrigerator:**

**Principle and working:** Refrigeration reduces metabolic activity and slows microbial growth, allowing suitable cultures and other temperature-sensitive materials to be stored for longer periods. Pure cultures may commonly be maintained at approximately 4°C for short-term storage, but this should not be generalized to every mushroom species (Sharma and Kumar, 2011).

**Conclusion**

Establishment of a mushroom spawn laboratory requires appropriate equipment, proper laboratory organization and strict aseptic practices. Equipment such as autoclave, laminar airflow cabinet, hot-air oven, incubator, pH meter and refrigeration facilities plays an important role in sterilization, culture maintenance, inoculation and spawn development. Proper selection, installation and operation of these facilities help minimize contamination and maintain the quality and consistency of mushroom spawn. A well-planned spawn laboratory can therefore support reliable spawn production for research, training and commercial mushroom cultivation.




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# KNOW YOUR SEED WITHOUT DESTROYING IT: EMERGING TECHNOLOGIES FOR RAPID SEED QUALITY ASSESSMENT

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**Abstract**

Good seed is the foundation of a good crop, yet most farmers cannot tell how strong their seed is until it fails in the field. Seed quality is fundamental to crop establishment, uniformity and productivity. Conventional seed testing methods, although reliable, can be time-consuming, destructive and sometimes poorly predictive of field performance. Emerging non-destructive technologies offer rapid alternatives for assessing seed quality and vigour. These include oxygen respiration analysis, chlorophyll fluorescence, soft X-ray imaging, machine vision, near-infrared spectroscopy, hyperspectral imaging, electronic noses and terahertz imaging. Artificial intelligence further improves classification accuracy by analysing complex seed characteristics. Despite their potential, cost, crop-specific validation and limited accessibility remain challenges. These technologies complement conventional testing, supporting efficient seed quality assessment and improved decision-making.

**Keywords :** Seed quality, Conventional methods, Non-destructive testing, Emerging technologies

## Introduction

Seed is a small share of the cost of cultivation, yet it determines how the rest of the crop performs. Many farmers save the seeds from their harvest or exchange it with neighbours and even purchased seed can give patchy germination, weak seedlings and costly gap-filling or re-sowing. Often the cause is not soil or weather but seed that looked sound and was not vigorous. A seed is a living embryo with its own food reserve, enclosed in a protective coat; in rice, wheat and maize, the whole grain is sown and is still called seed. Good seed makes four promises: a strong start (physiological quality, meaning rapid germination and sturdy seedlings), a true crop (genetic purity, with few off-types), a clean lot (physical purity, with minimal dirt, broken pieces or weed seed) and a healthy start (seed health, with low levels of seed-borne fungi, bacteria and insects). Seed moisture is equally critical, since moist seed ages quickly in storage. Conventional tests, such as germination counts, tetrazolium staining and vigour assays, are reliable but slow, laborious and destructive, because the tested seeds cannot be sown. Emerging non-destructive technologies now offer rapid alternatives: hyperspectral and near-infrared imaging, X-ray radiography, chlorophyll fluorescence sorting, machine vision with artificial intelligence, and portable sensors. These tools can predict viability, vigour, purity, damage and moisture within seconds, while leaving the tested seed intact.

## Why the old tests fall short

Traditional tests are valuable and still form the official basis of seed certification in India. Laboratories use physical tests (such as the purity working board), physiological tests (rolled paper towel and top-of-paper germination), biochemical tests (tetrazolium, accelerated ageing and electrical conductivity) and DNA-based tests. But they have limits:

- They spoil the seed - The tetrazolium test cuts and stains seeds to see if they are alive. Moisture is often measured by oven-drying. Germination tests leave sprouted seedlings that cannot be stored or sown. Accelerated ageing exposes seed to high heat and humidity to test its toughness.
- They take time - A germination test usually needs about 5 to 14 days, and longer for some crops, by which time the sowing window may be closing.
- They do not always match the field - A seed lot can pass the laboratory test and still emerge poorly in harsh soil.
- Losses add up - When seed is costly, as with hybrid vegetables or parental lines for hybrid seed production, even a small sample destroyed is a real loss.

This is why scientists are developing faster tools that leave the seed intact. Such non-destructive methods are rapid, reduce human error, leave the seed undamaged and cause no chemical change in it. Many are also automated, so large numbers of seeds can be checked at the same time. Below are the emerging technologies for rapid seed quality assessment.

**Listening to the seed breathe**

When a seed touches water, it wakes up and begins to breathe, using oxygen. A strong seed, like an athlete taking deep breaths before a race, starts using oxygen quickly. A weak or aged seed breathes slowly. The Q2 analyser measures this. Each seed sits in its own tiny sealed well with an oxygen-sensing spot. As the seed uses up the oxygen, the sensor signal changes, and the machine records how fast each seed is breathing. Fast breathers are usually strong and germinate early, while slow breathers point to an ageing lot. Research shows that oxygen use is closely linked with germination, so it can serve as an early indicator of vigour (Powell, 2017). Results can come in hours for many crops, though some tests run for a few days.

Farmers and seed producers should keep these cautions in mind - Dormant seeds or seeds with very hard coats (as in some pulses), can breathe slowly even though they are alive. The seeds are soaked during the test, so they are best sown soon rather than put back into storage. The test checks a sample of individual seeds, not the whole bag. So far, it has been used mostly in research, and reviews note that more work is needed on commercial seed lots.

**Spotting the glow of immature seed**

As a seed ripens on the mother plant, the chlorophyll (green pigment) in its coat breaks down. Seed harvested too early keeps some chlorophyll. When a machine shines light of a particular colour on such seed, the leftover chlorophyll gives off a faint glow that sensors can detect. This glow is red, not green. The glow does not harm the seed. It is simply a marker of immaturity, and immature seeds tend to age fast and store poorly. Chlorophyll fluorescence sorters read this glow and use a puff of air to remove immature seeds from the stream (Jalink *et al*., 1998). This method is mainly used for high-value seeds such as cabbage, mustard-family crops, carrot and tomato. It improves the evenness and storability of a lot, though it cannot promise perfect emergence.

**Seeing inside the seed**

A seed can look perfect outside and still be hollow or damaged inside. Soft X-ray imaging works like a hospital X-ray for seeds. It takes only about 3 to 5 seconds to produce an image, and the seed industry uses it to detect empty seeds, internal cavities, cracks, insect infestation and insect damage (Karunakaran *et al.,* 2004). It can show beetle larvae hiding inside chickpea and other pulse seeds,

and cracks caused by threshing machines. In a study on muskmelon seeds, X-ray imaging identified seeds with no cotyledons (seed leaves), cracks, large air spaces or irregular shapes, without changing the size or shape of the seed. Some seeds are sensitive to X-rays, however, so the method does not suit every crop.

**Teaching cameras to sort seed**

Machine vision acts like a pair of tireless eyes, using specialized lighting, cameras, and computers to judge each seed's shape, size, colour, and texture while filtering out damaged or off-type grains. While basic colour sorters date back to 1932, modern systems rely on high-resolution cameras and fast imaging software. By combining visible-light and X-ray images, researchers have successfully evaluated seed purity, viability, and vigour chemical-free in minutes—correctly classifying over 91% of tested soybean seeds.

**Reading seed with invisible light -** Seeds also interact with invisible light depending on their internal chemistry and viability :

- **Near-infrared (NIR) spectroscopy** estimates chemical compositions in seconds. It has been successfully used to measure oil and fatty acids in in-shell groundnuts and moisture levels in vegetable seeds.
- **Hyperspectral, multispectral and Raman imaging** blend photographs with light signatures to separate germinating seeds from dormant ones, classify castor seed viability, and even detect internal bacterial infections in watermelon seeds.
- **Seedling imaging**, such as Vigor-S developed in Brazil, photographs young seedlings and scores growth and uniformity in seconds. It works on germinated seedlings, so it makes testing objective but does not save the tested seed.

Ultimately, these automated computer imaging systems have become indispensable across the modern seed industry. They are widely used for DUS testing (checking a variety's distinctness, uniformity, and stability), identifying cultivars, sorting and grading batches, automating vigour testing, and detecting hidden defects.

**Smelling the seed: electronic nose and volatiles**

An ageing seed gives off a different smell. As stored seed deteriorates, its oils break down and it releases tiny amounts of volatile compounds: alcohols (a sign of fermentation), aldehydes (a sign of oil breakdown) and ketones (often linked to moulds and bacteria). The amount and mix of these compounds change with the extent of deterioration, so they can serve as an early warning (Suresh *et al.,* 2025). An electronic nose imitates the human nose with an array of gas sensors and pattern-recognition software, so it can 'smell' a sample of seeds quickly without damaging it. Researchers have used it to judge seed viability and to spot contaminants, and in groundnut the volatiles released during storage were tracked month by month as signatures of seed quality. There are cautions. A simple electronic nose picks up a mixture of smells rather than specific compounds, and its readings can drift with humidity and temperature.

**What's new: artificial intelligence and terahertz waves**- Two recent developments are making seed testing smarter and, in some cases, gentler on the seed.

Artificial intelligence (AI) - Cameras and light sensors generate huge amounts of data, and deep-learning software can learn to make sense of it. Combined with hyperspectral imaging, which captures how a seed reflects many different wavelengths of light, AI has become one of the leading

ways to judge seed vigour without damaging the seed. Another approach, which merged X-ray and hyperspectral data, predicted vigour with over 92% accuracy, beating either method on its own (Jin *et al.,* 2025).

Terahertz imaging - Terahertz waves range between microwaves and infrared light. Their low-energy, non-ionising radiation is considered safe for living seed, and it can pass through the seed coat or shell to reveal internal hidden defects and moisture patterns. When a neural network read terahertz images of peanuts, it correctly sorted five quality types with 98.7% accuracy (Jiang *et al.,* 2024). For now, this remains a laboratory technique, but it could be a useful alternative where X-rays might harm the seed.

**Limitations of the new tools**

Many of these machines are costly, need trained operators and are found mainly in research institutes, universities and larger seed companies. Some seeds are sensitive to X-rays and cannot be tested that way and many results so far come from research on single crops. They are meant to support official seed testing, not replace it. Because certification in India still relies on the standard germination, purity and health tests.

**Table 1: Comparison of conventional and newer seed quality tests**

| Method | Test duration | Is the seed still usable? | What it tells you |
|---|---|---|---|
| Standard germination test | About 5 to 14 days or more | No, seeds become seedlings | Germination % under ideal conditions |
| Tetrazolium/ accelerated ageing test | 1 to 3 days or more | No | Viability and ageing tolerance |
| Q2 oxygen test | Hours to a few days | Seeds are soaked; best sown soon | Early signal of vigour |
| Chlorophyll fluorescence sorting | Seconds (automated) | Yes | Removes immature seed; improves lot uniformity |
| Machine vision (camera) | Seconds to a few minutes | Yes | Size, shape and colour defects; sorting and grading |
| Soft X-ray | A few seconds per image | Yes (not for X-ray-sensitive seeds) | Hidden insects, cracks, empty seeds |
| NIR spectroscopy | Seconds | Yes | Moisture, oil, protein (needs calibration per crop) |
| Hyperspectral / multispectral imaging | Seconds to minutes | Yes | Viability, mould or bacterial infection (mostly research) |
| Terahertz imaging | Rapid | Yes | Internal defects, moisture, vigour (laboratory stage) |
| Electronic nose (volatiles) | Rapid | Yes | Early ageing and spoilage signals in stored seed (research stage) |

**Conclusion**

Seed quality sets the ceiling for the harvest and no amount of fertilizer, good weather or costly crop protection can fully make up for weak seed. New tools that detect seed respiration, read the glow of immature seed, smell the early signs of ageing and look at seed with cameras, X-rays and invisible light can flag weak lots within hours or seconds and save valuable seed from being destroyed in testing. They only support, but do not replace the certified seeds, official testing and good storage. Until they reach villages, simple steps such as buying tagged seed, doing a home germination test (100 seeds in a damp cloth, counted after 5 to 10 days) and storing seed dry and cool remain the farmer's best protection. For costly or hybrid seed, the nearest Krishi Vigyan Kendra or seed testing laboratory can advise on available tests. As equipment becomes smaller and cheaper, Farmer Producer Organisations (FPOs), seed processing units and custom hiring centres may one day offer quick quality checks. That is a hope for the future, not yet an everyday reality.

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# FISH FARMING THROUGH BIOFLOC TECHNOLOGY

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**Abstract**
Biofloc technology is a new-age aquaculture practice that's stressing developing and preserving an environment in water supporting the growth and health of fish bred in captivity, in real-world scenarios. Indeed, the diverse micro-organisms in the ecosystem, like algae, bacteria. Biofloc is a collection of organic and inorganic microscopic elements existing in water. The term "biofloc" is obtained from two words: "bio," meaning living, and "floc," meaning a clump or combine, in actual application. And plankton taken from living organisms (on land and sea), organic matter, and inorganic matter including polymers and dead cells, form clumps. They're protein-rich clumps. Bioflocs are, as a matter of fact, mostly microscopic, measuring 50-200 microns. Biofloc fish farming is a method that's somewhat new in the field of aquaculture. It's also a waste-management process through the which fish waste and other aquatic-animal refuse are converted, in conjunction with bacteria, into the protein-rich food that fish are able to eat, and is considered environmentally friendly. Fish can, to be sure, be created employing less space, less water, and at a lower cost.

**Introduction**
The global population growth, urbanization, economic development, and dietary diversification have raised the demand for aquatic foods. According to the FAO, in 2022, global apparent consumption of aquatic animal foods reached approximately 165 million tonnes, and aquatic foods contributed about 15% of the total animal protein intake worldwide; it is estimated that to fulfil current per-capita aquatic-food consumption through 2050, an additional 36 million tonnes of supply will be needed. The expansion of traditional aquaculture practices, such as pond culture, places substantial pressure on water, land, feed, and surrounding ecosystems. FAO indicates efficient use of water, land, feed, energy and nutrient-management practices as vital for sustainable aquaculture intensification, on the whole. (*FAO.*, 2024) In conventional intensive aquaculture systems, uneaten feed, faeces and metabolic products pile up in the culture system (McCusker *et al*., 2023). They include organic matter, suspended solids, residual feed, nutrients and microbial contaminants. Without ample management, these materials may, after all, contribute to eutrophication and also guide to water-quality deterioration. (Ojewole *et al*., 2024).

Nutrient emissions from ponds and habitat conversion are some of the issues associated with some aquaculture production systems, all things considered. Aquaculture expansion is directing to land-use pressures. (Hammarlund *et al*., 2024). Aquaculture expansion is directing to land-use pressures. Nutrient emissions from ponds and habitat conversion are some of the issues associated with some aquaculture production systems, all things considered, in the main. (Mugwanya *et al*., 2021). Biofloc technology is an intensive aquaculture method where helpful microorganisms convert fish waste into the protein-rich microbial biomass that can be consumed by cultured fish, at least for now. The core principle covered in BFT is mainly managing the carbon-to-nitrogen ratio by the addition of

organic carbon. This can also be done by increasing dietary carbon content, which findings in the growth of heterotrophic bacteria as well as assimilation of inorganic nitrogen into the microbial biomass, in the main. (Li *et al*., 2023) The made microbial biomass in BFT is offering a extra feed source that includes protein and other nutrients, in actual application, and microbial biomass is helping to regulate nitrogenous compounds and support water quality. (Raza *et al*., 2024)

**Concept and Principle of Biofloc Technology**

Bio is being combined by The term biofloc, meaning living organisms, and floc, meaning aggregated particles or clumps, at least empirically. In aquaculture, bioflocs are normally suspended combines formed from microorganisms and organic particles in the culture water, broadly speaking. (McCusker *et al*., 2023) , They encompass bacteria, microalgae, protozoa, fungi, zooplankton, organic matter, inorganic particles, and dead cells. (Khanjani *et al*., 2022)The preparation of biofloc entails a systematic sequence of tank preparation, aeration, water conditioning, pH regulation, and microbial inoculation. Indeed, nutrient recycling and water-quality management is being supported by these components.

**Preparation of Biofloc**

**Step 1: Filling Water Tank with Water**

↓

**Step 2: Soaking New Air Stones/Aeration Tubes**

Soaked in water for 3–4 hours before installation, if new.

↓

**Step 3: Continuous Aeration**

Maintaining aeration for 24 hours.

↓

**Step 4: Adding Salt**

Dissolving salt in water separately and add gradually to the tank.

↓

**Step 5: Adding Calcium Carbonate**

After 3 hours, mix calcium carbonate with water and add it to the tank.

↓

**Step 6: Check and Adjust pH**

If pH is below 7.0: Add slaked lime mixed with water, gradually, and recheck pH.
If pH is above 8.0: Add diluted molasses and distribute uniformly; monitor pH.
If pH is between 7.0 and 8.0: Proceed to the next step.

↓

**Step 7: Adding Aquatic Probiotics**

Mix with water and distribute uniformly throughout the tank.

↓

**Step 8: Maintaining Continuous Aeration**

Ensure adequate dissolved oxygen and uniform mixing.

↓

**Biofloc Preparation Process Completed**

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**Working Mechanism of the Biofloc System**

In biofloc, fish feed is the central input. Fish consume this matter for growth and metabolism, at least in practice. And thus, in this process, fish release metabolic waste, which consists mainly of ammonia, through the excretion, broadly speaking. Beyond that, unconsumed feed, droppings and decaying organic matter add nitrogenous substances to the culture water, which is augmenting the total nitrogen load in the framework (Yu *et al*., 2023). Indeed, when the carbon source is added to the system, heterotrophic bacteria use inorganic nitrogen, like ammonia, as a nutrient source for microbial growth. This microbial activity decreases dissolved nitrogenous waste to microbial biomass, driving growth of suspended microbials (bioflocs) (Khanjani *et al*., 2022). It is made up of bacterial cells, organic particles, algae, and other microorganisms that can be eaten by the cultured fish and shrimp species. So, biofloc functions as a complementary natural protein supply that helps in nutrient recycling and enhancement of water quality (Emerenciano *et al*., 2017)

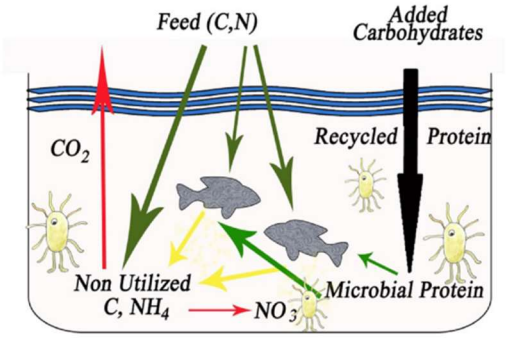



***Fig: Schematic overview of the working principle of the biofloc technology.***

**Materials and preparation of a biofloc**

The construction of biofloc requires the following:

| No. | Item | Brief explanation | References |
|---|---|---|---|
| 1 | Tank | Holds the culture water, fish and biofloc. Tanks should, after all, probably allow effective circulation and aeration, broadly speaking. | *Biofloc Production Systems for Aquaculture*, 2013 |
| 2 | Tarpaulin | Waterproof liner placed inside a tank frame to prevent leakage and provide a smooth culture surface. | *Biofloc Production Systems for Aquaculture*, 2013 |
| 3 | Iron mesh | Offers structural support for a tarpaulin tank and helps it keep its shape. | (Ogello *et al*., 2021) |
| 4 | Air blower | Creates continuous airflow for aeration, water mixing, and suspension of bioflocs. | Khanjani *et al*., 2024 |
| 5 | Air stone | Releases air as fine bubbles, increasing oxygen transfer and sharpening water circulation. | Khanjani *et al*., 2024 |
| 6 | Oxygen pipe | Transfers air from the blower to air stones or diffusers in the tank. | (Ogello *et al*., 2021) |

| No. | Item | Brief explanation | References |
|---|---|---|---|
| 7 | Inverter | Battery power was, as a matter of fact, stored into the electricity by converts to operate aeration equipment during a power outage, at least for now. | *Biofloc Production Systems for Aquaculture*, 2013 |
| 8 | PVC pipe | Employed for water inlet, drainage and overflow, especially for air-distribution connections. | (Ogello *et al*., 2021) |
| 9 | Battery | Stores backup electricity for critical equipment, chiefly the air blower. | *Biofloc Production Systems for Aquaculture*, 2013) |
| 10 | Ammonia test kit | Measures ammonia concentration, allowing early detection of potentially toxic nitrogen accumulation. | (Matishov *et al*., 2025) |
| 11 | Nitrite test kit | Measures nitrite concentration. High nitrite levels can (to a meaningful extent) be harmful to cultured fish. | (Matishov *et al*., 2025) |
| 12 | pH test kit | Measures water acidity or alkalinity. PH impacts fish health and microbial processes. | (Matishov *et al*., 2025) |
| 13 | Alkalinity test kit | Measures the water's buffering capacity and helps prevent sudden pH fluctuations. | *Biofloc Production Systems for Aquaculture*, 2013) |
| 14 | Dissolved oxygen (DO) test kit | Measures oxygen available for fish and microorganisms. | (Khanjani *et al*., 2024) |
| 15 | Probiotics | Helpful microbial preparations employed to support microbial balance and organic-waste decomposition. | (Matishov *et al*., 2025) |
| 16 | Calcium carbonate | Employed as a liming material to increase alkalinity and help stabilize pH. | *Biofloc Production Systems for Aquaculture*, 2013 |
| 17 | Molasses | A easily available carbon source that's supporting heterotrophic bacteria and biofloc formation by increasing the carbon-to-nitrogen ratio, at least for now. | Khanjani *et al*., 2024 |
| 18 | Rock salt | Can maybe be employed to adjust salinity or support osmoregulation, resting on the fish species and farming conditions, on the whole. | (Matishov *et al*., 2025) |
| 19 | Inlet cone | Directs incoming water into the tank and can (at least in most settings) likely help uphold circulation while lessening disturbance to fish and flocs, all things considered. | *Biofloc Production Systems for Aquaculture*, 2013 |

| No. | Item | Brief explanation | References |
|---|---|---|---|
| 20 | Thermometer | Measures water temperature, which is altering fish metabolism, microbial activity, and dissolved oxygen. | (Matishov *et al*., 2025) |
| 21 | Hand net | Employed to collect, transfer, sample, or harvest fish and remove unwanted material from the tank, at least empirically. | (Matishov *et al*., 2025) |

**Water-quality parameters in Biofloc**

Water-quality limits are encompassing monitoring temperature pH, dissolved oxygen, nitrogenous wastes, salinity, and alkalinity. Slaked lime can be employed when pH is usually very low and needs to be raised quickly. Molasses to bring it back into the balance, if pH rises in biofloc above 9.0. Another essential guideline is often pH, which needs to be roughly 6.8-8.0. A drop in pH below 7.0 can lower nitrification efficiency (Nisar *et al*., 2022). Management is a vital part of biofloc management because these factors jointly impact cultured animals and the microbial community (Ahmed Alkhamis *et al*,. 2023). For tropical biofloc culture, 28-30 °C is essential. Cooler temperatures around 20 °C may decrease microbial/floc development (Muthoka *et al*., 2026; Panigrahi *et al*., 2021). Next parameter is maintain Dissolve Oxygen above 4.0 mg/L at minimum; a target above 6.0 mg/L Which provides an additional safety margin in intensive tanks with high aeration demand, Total ammonia nitrogen (TAN) below 1.0 mg/L; is preferable and its Toxicity is strongly affected by pH and temperature because these determine the proportion of toxic unionized ammonia, and recommends alkalinity above 100 mg/L supports nitrogen assimilation and nitrification. (JAMAL *et al*., 2020). Managing salinity in biofloc systems depends upon cultured species 0–50 ppt (Emerenciano *et al*., 2017).

**Advantages of Biofloc Technology**

Benefits from Biofloc Technology can be divided into three segments i.e., Environmental Benefits, Economic Benefits, Production Benefits. Environmental Benefits include reduced water exchange by maintaining water quality by recycling nutrients within the same culture unit, which result in reducing the need for frequent water replacement. (Raza *et al*., 2024) Another benefit is converting waste into useful biomass. The heterotrophic microorganisms present in biofloc assimilate nitrogenous waste, such as ammonia, and convert it into microbial biomass which is then consumed by cultured fish or shrimp. (Mugwanya *et al*., 2021) Biofloc systems may also reduce nutrient discharge and environmental pollution as compared to conventional systems. Because water exchange is limited, biofloc systems reduce the release of nutrient-rich effluent directly into surrounding water bodies. (Khanjani *et al*., 2024) Next Sector of Benefits is Economical Benefit ,Bioflocs system provide microbial protein and other nutrients natural food, which causes partial reductions in external feed inputs (Oliveira *et al*., 2022), Biofloc systems are intensive in culture which can support higher biomass production which is production per unit area or volume (Mugwanya *et al*., 2021) Production benefits includes improve fish growth and feed conversion Ratios (Yu *et al*., 2023)Biofloc technology support intensive culture systems which high stocking densities in fish and shrimp (Oliveira *et al*., 2022).

**Suitable Fish Species for Biofloc Culture**

Tilapias (*Oreochromis spp*.) represent one of the most broadly employed types of freshwater fish for aquaculture using bioflocs due to their capacity to consume biofloc microbial combines by

means of filter feeding (Raza *et al*., 2024), in the main. And thus, nile tilapia will betterly run in bioflocs that are well-managed, even with very high stocking levels (L. K. Oliveira *et al*., 2022), all things considered. Though, tilapias are generally resistant to many different infectious diseases, high-density culture can guide to augmented risk of disease development if stocking density and/or water quality aren't managed correctly (Zabidi *et al*., 2021). The striped catfish, also known as Pangasius (*Pangasianodon hypophthalmus*), is a second species that's well suited for biofloc based aquaculture. Biofloc polyculture systems using Indian major carps such as rohu (*Labeo rohita*) and catla (*Catla catla*) have been showed to be possible (Deb *et al*., 2020). Indeed, as, well, a research study showed typical carp (*Cyprinus carpio*) reared under the biofloc conditions with higher stocking densities betterly grew and feed conversion than carps reared in standard clear-water culture under the controlled conditions (Adineh *et al*., 2019). Honestly, research has assessed the effect of stocking density on Pangasius performance and findings show that it can (to a meaningful extent) be intensively farmed in tanks with proper management of the C:N ratio and water quality (Vaishali *et al*., 2024).

**Conclusion**

The future development of biofloc technology will rely heavily upon its increased use by small-scale and large-scale fish farmers. In order for this to occur, there will need to be better technical training available to farmers, more affordable biofloc system designs developed, and alternatives to the large investments in equipment and high energy usage that are required initially Solar power and/or biogas are two possible alternatives to continuous aeration and water circulation that may help lower operational expenses related to electricity consumption. Additionally, using IoT sensors, automated feeders, and artificial intelligence-driven predictive models may assist farmers in better managing biofloc systems through real-time monitoring of water quality. Biofloc systems can be combined with aquaponics systems (flocponics) to provide farmers with opportunities to reuse nutrients while growing both fish/shrimp and hydroponic plants in the same system. Overall, biofloc technology provides significant opportunity to promote water conservation, nutrient recycling, reduced effluent discharge, and improved resource utilization in aquaculture, thereby contributing to the creation of circular, sustainable, and climate resilient aquaculture . When managed effectively, and with continued innovation in technology and increased access for farmers, biofloc technology can make a substantial contribution to enhancing food security and promoting environmentally responsible development of aquaculture.

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# FROM MYTH TO REALITY: THE COMPLEX SCIENCE OF PLANT TISSUE CULTURE

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Have you ever seen pictures of tiny plants growing inside glass bottles and thought, “How easy that looks?” Many people believe plant tissue culture is almost like magic. You cut a small piece of a plant, put it in a jar with some special jelly, and within a few weeks a new plant appears. It sounds simple, clean, and reliable.

Unfortunately, the reality inside research laboratories is very different.

In actual practice, many of these cultures get infected by invisible bacteria or fungi. The plant pieces often turn brown and die. Sometimes shoots grow but roots never appear. Even when a plant looks healthy inside the bottle, it may collapse and die the moment it is transferred to soil. These failures are extremely common, and they happen for deep biological reasons. At the centre of tissue culture is a remarkable ability of plant cells. Almost every living plant cell contains the complete set of instructions needed to make an entire plant. Scientists call this totipotency. In theory, a single cell can become a full plant. In practice, however, this process is tightly controlled by the plant’s own hormones, genes, and stress responses. Getting the balance right is far from easy.

Two plant hormones play a starring role i.e., auxin and cytokinin. Their relative amounts decide whether the tissue will form roots or shoots. Scientists discovered this important relationship many decades ago. They also developed a standard nutrient medium that works for many plants. These discoveries made tissue culture possible. But they did not make it simple.

Different plants behave very differently in the laboratory. Plants like tomato and broccoli are relatively easy to grow win the lab. With careful work, researchers can regenerate them successfully. But some plants are stubborn. Scientists call them “recalcitrant.” The rare Himalayan medicinal plant *Fritillaria roylei* (Jangli lahsun) and walnut trees are classic examples. Even after years of experiments, getting these plants to regenerate reliably remains a major challenge. Contamination is one of the biggest challenges. The nutrient jelly that feeds the plant tissue is also perfect food for microbes. Cleaning the surface of the plant piece removes many germs, but bacteria and fungi living inside the plant tissue often survive and appear later. Another common problem is browning. When certain plants are cut, they release chemicals that turn dark and toxic, slowly poisoning the tissue. Researchers try to control this with charcoal or antioxidants, but success still depends heavily on the particular plant being used.

Even after shoots and roots form, the final step is often the most complex. Plants grown inside closed bottles develop soft leaves and weak roots because they live in high humidity with a constant supply of sugar. When suddenly exposed to normal air, sunlight, and soil, many of them cannot cope and die. This stage, called hardening or acclimatisation, needs great care.

The biggest lesson from all this experience is clear: every plant has its own biological personality. What works beautifully for tomato may completely fail for walnut. There is no single magic recipe that works for all plants. Scientists must carefully test different plant parts, hormone combinations, and growing conditions for each new species or variety.

When the right conditions are finally found, tissue culture becomes a powerful tool. It can produce large numbers of healthy, disease-free plants for farmers, help save rare medicinal species, and support plant breeding. But this success comes only after respecting the plant's own biology.

The popular image of a plant piece magically turning into a full plant inside a glass jar is attractive. The real science, however, is far more complex, demanding, and fascinating. Plant tissue culture is not a simple technique. It is a precise biological craft that rewards patience, careful observation, and deep respect for living plants.

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# GILOY (*Tinospora cordifolia*): A VALUABLE MEDICINAL PLANT FOR HEALTH AND VALUE-ADDED PRODUCT DEVELOPMENT

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**Introduction**

Medicinal plants have been an integral part of India's agricultural heritage and traditional healthcare systems for centuries. Their importance has increased considerably with growing scientific interest in plant-derived bioactive compounds, sustainable utilization of natural resources and the development of innovative value-added products. Among the various medicinal plants, Giloy (*Tinospora cordifolia*), commonly known as Guduchi, Amrita or Heart-leaved Moonseed, occupies an important position in traditional Indian medicine. It is a perennial climbing shrub belonging to the family Menispermaceae and is widely distributed across tropical and subtropical regions of India (Saha & Ghosh, 2012).

Giloy is characterized by its climbing stems, distinctive heart-shaped leaves and aerial roots. The plant commonly grows over trees and other supporting structures. The Giloy (*Tinospora cordifolia*) plant showing characteristic heart-shaped leaves and climbing stems is illustrated in Fig. 1. The different plant parts of Giloy, including (a) leaf, (b) stem, (c) flower and (d) fruits, are presented in Fig. 2. The stems are frequently utilized in traditional herbal preparations, while different plant parts contain several classes of phytochemical constituents, including alkaloids, glycosides, diterpenoid lactones, phenolic compounds and polysaccharides (Sharma et al., 2019).

Scientific investigations have examined Giloy for its antioxidant, anti-inflammatory and immunomodulatory activities, primarily through laboratory and preclinical studies. However, these reported biological properties should not be interpreted as confirmed therapeutic benefits in humans. Variations in growing conditions, plant maturity, harvesting practices and processing techniques may also influence the composition and quality of the raw material (Chaudhary et al., 2024).

From a food processing perspective, Giloy offers opportunities for investigating dried herbal powders, extracts, instant premixes and other value-added formulations. Technologies such as controlled drying, grinding, extraction and spray drying may help develop standardized ingredients with desirable handling and storage characteristics. Sarala et al. (2012) demonstrated the preparation of Giloy leaf and stem extract powders through spray drying, indicating the potential application of modern processing technologies.

Nevertheless, the development of Giloy-based products requires careful consideration of raw material authentication, physicochemical quality, sensory acceptability, packaging, microbial safety and storage stability. Furthermore, published reports of liver injury associated with Giloy

consumption emphasize the importance of toxicological evaluation and responsible product development (Kulkarni et al., 2022). Therefore, integrating traditional knowledge with scientific processing methods, quality-control procedures and appropriate safety assessments is essential for exploring the potential of Giloy in value-added product development.



***Fig. 1. Giloy (Tinospora cordifolia) plant showing characteristic heart-shaped leaves and climbing stems.***



***Fig. 2. Different plant parts of Giloy (Tinospora cordifolia): (a) Leaf, (b) Stem, (c) Flower And (D) Fruits.***

**Botanical Characteristics and Phytochemical Composition of Giloy**

Giloy (*Tinospora cordifolia*) is a perennial, deciduous climbing shrub belonging to the family Menispermaceae. It is commonly found in tropical and subtropical regions and grows naturally over trees, shrubs and other supporting structures. The plant possesses long, succulent stems with a characteristic greyish-green appearance, heart-shaped leaves and aerial roots. Its small greenish-yellow flowers develop in clusters, while the fruits become reddish upon maturity. The stem is among the most commonly utilized plant parts in traditional preparations, although leaves and roots have also been investigated for their phytochemical properties (Saha & Ghosh, 2012).

The phytochemical composition of Giloy contributes to its scientific importance. Various studies have identified alkaloids, diterpenoid lactones, glycosides, steroids, phenolic compounds and polysaccharides in different plant parts. Important reported constituents include berberine, magnoflorine, tinosporaside, cordifolioside derivatives and other secondary metabolites. These compounds have been studied for their potential biological activities, although their concentrations

and properties depend on plant maturity, geographical location, environmental conditions and extraction techniques (Sharma et al., 2019).

From a processing perspective, the variability of phytochemical constituents highlights the importance of raw material selection and standardization. Drying temperature, particle size, extraction conditions and storage environment may influence the quality of processed Giloy materials. Therefore, appropriate processing methods and analytical evaluation are necessary to develop consistent herbal powders, extracts and experimental value-added formulations (Sarala et al., 2012).

Correct botanical identification is equally important because closely related *Tinospora* species may differ in their chemical composition and safety profiles. Consequently, phytochemical characterization, botanical authentication and appropriate safety assessment should form essential components of Giloy-based product development.

**Postharvest Handling and Processing of Giloy**

Proper postharvest handling and processing play an important role in maintaining the quality of medicinal plant materials. In the case of Giloy (*Tinospora cordifolia*), processing begins with the selection of correctly identified, healthy and mature plant material. The stems are commonly selected for processing because of their traditional importance and reported phytochemical constituents. After harvesting, the stems should be sorted to remove damaged or deteriorated portions, thoroughly cleaned to eliminate adhering soil and foreign materials, and cut into uniform pieces to facilitate subsequent processing.

**Drying of Giloy:** Drying is an important preservation technique used to reduce moisture content and improve the storage stability of plant materials. Traditional shade drying and controlled mechanical drying are potential approaches for processing Giloy stems. Controlled drying offers opportunities for improved process consistency, although suitable temperature and drying duration must be established experimentally. Excessive heat exposure may adversely affect heat-sensitive constituents, while inadequate drying can increase the risk of microbial deterioration. Therefore, optimization of drying conditions is necessary to obtain stable raw materials without unnecessary quality losses.

**Grinding and Powder Preparation:** After drying, Giloy stems can be reduced to powder using suitable grinding equipment. The resulting material may be sieved to obtain a relatively uniform particle size, which can improve mixing and handling during formulation. In addition to conventional grinding, extraction followed by spray drying offers another approach for preparing powdered ingredients. Sarala et al. (2012) investigated spray drying of Giloy leaf and stem extracts and evaluated the antioxidant properties of the resulting powders.

**Packaging and Storage:** Dried Giloy powder should be handled hygienically and packed in suitable moisture-resistant containers to minimize moisture absorption and contamination. Product quality can be evaluated through moisture content, water activity, colour, microbial load and selected phytochemical characteristics. Appropriate packaging and storage conditions should be established through systematic shelf-life studies rather than assumed from the drying method alone.

The integration of standardized postharvest practices, controlled drying and suitable packaging can support further research into Giloy-based value-added formulations. However, product

development intended for consumption must also include botanical authentication, contaminant testing, safety evaluation and compliance with applicable regulations.

**Value-Added Products From Giloy**

Value addition of medicinal plants offers opportunities to transform agricultural raw materials into convenient and standardized products. Giloy (*Tinospora cordifolia*) has attracted interest as a potential ingredient for herbal formulations because of its diverse phytochemical constituents. However, the development of Giloy-based products requires scientifically validated processing methods, appropriate safety assessments and careful evaluation of product quality.

**Giloy Powder and Extracts:** Dried Giloy stems can be processed into fine powder through grinding and sieving. The resulting powder provides a convenient material for research on herbal formulations. Giloy extracts may also be converted into powdered ingredients using technologies such as spray drying. Sarala et al. (2012) investigated the preparation of spray-dried Giloy leaf and stem extracts, demonstrating the technical feasibility of producing powdered extracts.

**Herbal Premix Development:** Giloy powder may be investigated in experimental herbal premixes containing ingredients such as ginger, tulsi, jaggery and black pepper. These ingredients can influence the flavour, colour, texture and physicochemical characteristics of a formulation. Different ingredient proportions should be evaluated for mixing uniformity, sensory acceptability, moisture content, water activity and storage stability. Such formulations should remain research products until their safety and regulatory suitability for consumption have been established.

**Extract-Based Product Development:** Giloy extracts may also be investigated in combination with fruit-derived ingredients and other plant materials. The selection of extraction and drying conditions is important because these processes can influence powder characteristics and the retention of selected phytochemical constituents. Formulation studies should therefore evaluate processing performance alongside ingredient compatibility and product stability.

**Quality Evaluation, Packaging and Storage Stability of Giloy-Based Products**

Quality evaluation is an essential step in developing standardized Giloy (*Tinospora cordifolia*)-based formulations. The quality of herbal powders and premixes depends on raw material characteristics, processing conditions, ingredient proportions and storage environment. Systematic assessment of physicochemical, microbiological and sensory properties is therefore necessary to maintain product consistency and evaluate changes during storage.

**Physicochemical Quality:** Important parameters include moisture content, water activity, pH, titratable acidity, colour and selected phytochemical constituents. Moisture content and water activity are particularly relevant to dried powders because they influence microbial growth potential, powder stability and moisture-related deterioration. Changes in colour and other quality attributes may also indicate the effects of processing or storage conditions.

**Microbiological and Sensory Evaluation:** Microbial testing helps assess the hygienic quality of raw materials and processed formulations. Appropriate examinations may include aerobic plate counts and testing for relevant yeasts, moulds and pathogens. Sensory evaluation can provide information about appearance, aroma, taste and overall acceptability, but tasting trials should only be conducted after the formulation has undergone appropriate safety assessment.

**Packaging and Storage Stability:** Moisture-resistant, food-grade packaging materials may help protect dried herbal formulations from environmental humidity and contamination. Packaging selection should consider barrier properties, product compatibility and intended storage conditions. Periodic evaluation of product quality during storage is necessary to identify deterioration and establish a scientifically supported shelf life.

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# FROM MAPPING FIELDS TO PREDICTING FUTURES: GIS AND ARTIFICIAL INTELLIGENCE IN INDIAN AGRICULTURE

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**Abstract**
Agricultural maps in India have long recorded where crops are grown. Satellite remote sensing, Geographic Information Systems (GIS) and machine learning now allow those maps to estimate crop condition, area and yield while the season is still under way. This article explains how the three technologies work together as a single pipeline, and how field-verified ground truth links them. It then reviews operational Indian applications: crop forecasting under FASAL, drought assessment under NADAMS, technology-based yield estimation for crop insurance under YES-TECH, and the Krishi-DSS platform. Reported accuracies in Indian studies range from about 75 to 96 per cent, which points to real limits in data quality, transfer across regions, interpretability and the delivery of advice to farmers. The article closes with a framework that combines open data, local validation, extension workers and accessible tools.

**Keywords:** GeoAI, remote sensing, crop forecasting, crop insurance, Krishi-DSS

## Introduction: The Changing Role of Maps

For most of their history, agricultural maps have described rather than predicted. They showed where crops were grown, how land was divided and which areas depended on canals or rain. They served administration well, but they captured a single moment and said little about how a crop might fare over the rest of the season.

Knowing where a crop is growing is a question of location. Anticipating how it will perform is a question of prediction, and the answer depends on rainfall, soil moisture, temperature, crop health and farm management, all changing at once. In a monsoon-dependent country, early estimates of crop condition shape procurement, disaster relief and insurance claims.

Two technologies make the shift from location to prediction possible. GIS organises spatial data, and artificial intelligence (AI), mainly machine learning, finds patterns in that data and turns them into estimates. This article explains how they work together, reviews their use in Indian agriculture, and examines where they fall short.

## GIS Meets AI: An Integrated Pipeline

### Spatial data in layers

A GIS stores information about places as a stack of aligned layers, each describing one property of the same ground, such as crop type, soil class, rainfall or irrigation. *Raster* layers divide the land into a grid of cells, as in a satellite image. *Vector* layers hold points, lines and boundaries, such as field or village limits. Because all layers share one coordinate system, each location carries a value from every layer.

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**Remote sensing: optical and radar**

Satellites supply most of these layers. Optical sensors record reflected sunlight, and the best-known measure derived from them is the Normalised Difference Vegetation Index, NDVI = (NIR − Red) / (NIR + Red), where NIR is near-infrared reflectance. Higher values indicate denser, greener crops. Optical sensors cannot see through cloud, however, and the *kharif* crop grows under monsoon skies. Synthetic Aperture Radar (SAR) avoids this problem by sending out its own microwave pulse, which allows imaging by day or night in any weather. India's EOS-04 (formerly RISAT-1A) carries a C-band SAR, and agriculture is listed among its main applications[8]. Table 1 compares the sensors most used for Indian crop monitoring.

**Table 1. Optical and radar sensors used in Indian crop monitoring**

| Satellite | Sensor type | Spatial resolution | Sees through cloud | Main agricultural use |
|---|---|---|---|---|
| Sentinel-2 (ESA) | Optical, multispectral | 10 m | No | NDVI, crop health |
| Resourcesat-2A, LISS-IV (ISRO) | Optical | 5.8 m | No | Field-level crop inventory |
| Sentinel-1 (ESA) | C-band SAR | 10 m, revisit every 12 days | Yes | Rice mapping, sowing dates |
| EOS-04 / RISAT-1A (ISRO) | C-band SAR | 1 to 50 m by imaging mode | Yes | Monsoon-season crop monitoring |

**Machine learning as the interpreter**

NDVI is a fixed formula. A machine learning model, by contrast, learns its own rules from examples. It is trained on locations where the crop is already known and then applied to the rest of the image. Random Forest and Support Vector Machine classifiers are widely used to separate crop types, convolutional neural networks extract spatial patterns, and recurrent models such as LSTM networks track how a crop's signal changes across a season. In Guntur district, a Random Forest model trained on Sentinel-1A data and 84 field observations mapped rice with 94 per cent user's accuracy and 96 per cent producer's accuracy[11].

**Data fusion and the GIS–AI loop**

Models can combine optical, radar, soil and weather layers in one analysis. In Chhattisgarh, a model that fused Sentinel-1 and Sentinel-2 time series separated direct-seeded from transplanted rice with 77.3 per cent overall accuracy and clearly outperformed single-sensor models[13].

The link between GIS and AI runs in both directions (Figure 1). GIS supplies the model with aligned inputs and *ground truth*, the field-verified records of what is actually grown where. The model's outputs, such as a crop map or a yield estimate, then return to the GIS as new layers that officials can view and test against official statistics. This combined field is often called GeoAI.

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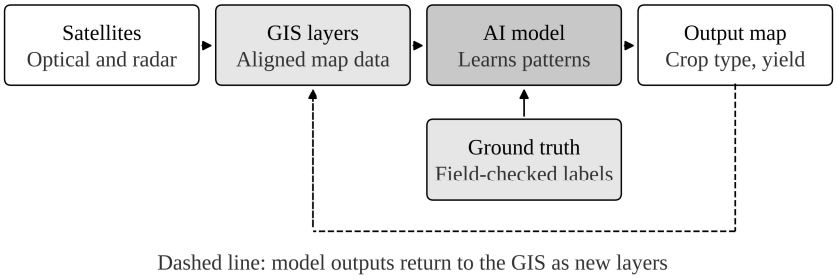



***Figure 1. The GIS–AI pipeline and its feedback loop (Source: Authors' illustration)***

**Applications in Indian Agriculture**

**Crop monitoring and acreage**

The Mahalanobis National Crop Forecast Centre (MNCFC) was set up in 2012 to prepare in-season crop forecasts from satellite imagery and to assess drought[4]. Under the FASAL programme, it applies remote sensing methods developed by ISRO's Space Applications Centre, which have so far been transferred for eight crops, including wheat, *kharif* rice, cotton, jute, sugarcane and rapeseed-mustard[1]. Radar has made in-season tracking practical. In Kakinada district, Sentinel-1 estimates of transplanted rice area in 2023 stayed within 3 per cent of Agriculture Department records on each of four dates[12].

**Yield and production forecasting**

FASAL does not depend on a single yield model. Remote sensing estimates are combined with agro-meteorological forecasts from the India Meteorological Department and with econometric forecasts[1]. ISRO's newer CROP framework, built by the National Remote Sensing Centre (NRSC) for near real-time monitoring of *rabi* sowing and harvest, estimated wheat production in the eight major producing states at 122.724 million tonnes as of 31 March 2025[3].

**Drought assessment**

Since 2012, MNCFC has assessed agricultural drought under the National Agricultural Drought Assessment and Monitoring System (NADAMS), using NRSC methods[10]. Under the 2016 drought manual, rainfall deviation and dry spells trigger an assessment, impact indicators such as satellite vegetation indices and soil moisture grade its severity, and states verify severe findings on the ground[10]. Krishi-DSS adds a drought module that reports soil moisture, water storage, crop condition and dry spells[9].

**Technology-enabled crop insurance**

Under the Pradhan Mantri Fasal Bima Yojana (PMFBY), yields have traditionally been measured through manual crop-cutting experiments. From *kharif* 2023, the Yield Estimation System based on Technology (YES-TECH) has assigned a mandatory 30 per cent weight to technology-derived yields for paddy and wheat, and soybean was added from *kharif* 2024[5]. Madhya Pradesh went further and gave technology-based estimates full weight for selected crops[6]. Results so far are mixed. A Haryana implementation reported accuracy of 75 to 95 per cent[2], while a review of the Madhya Pradesh experience recorded farmer dissatisfaction with claim outcomes. That review also judged technology-based yields to be more transparent than manual estimates[6].

**Krishi-DSS as an integrating platform**

These strands meet in Krishi-DSS, a geospatial platform launched by the Ministry of Agriculture and Farmers Welfare on 16 August 2024 and built on RISAT-1A data and the Department of Space's

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VEDAS system. Its modules include parcel-level crop maps across years, field parcel segmentation, a national soil information system and a ground-truth data library that offers field data and crop spectral libraries to researchers and industry[9]. In terms of the GIS–AI loop, the library may be its most important feature, because the quality of ground truth limits every model trained on it. Table 2 lists the main public platforms.

**Table 2. Indian geospatial platforms for agriculture**

| Platform | Operated by | Main function | Scan to open |
|---|---|---|---|
| Bhuvan | ISRO (NRSC) | National geoportal hosting public geospatial data as map layers | |
| VEDAS | ISRO (SAC) | Visualisation and analysis of earth observation data for decision support | |
| MOSDAC | ISRO (SAC) | Distribution of satellite mission data in near real time | |
| Krishi-DSS | MoA&FW with Department of Space | Integrated crop, soil, water and drought decision support | |

**The Limits of Prediction**

Four limitations stand out, each a weak point in the loop shown in Figure 1.

**Data quality**

A model is only as reliable as its inputs. Optical data is lost to monsoon cloud, and radar has blind spots of its own: in Guntur, waterlogged fallow land and self-sown rice gave radar signals similar to cultivated rice and inflated area estimates[11]. Ground truth is the deeper constraint. In the Chhattisgarh study, enlarging the training set from 92 to 152 fields raised the model's recall for direct-seeded rice from 0.65 to 0.79[13]. Such field data is slow and costly to collect.

**Regional generalisation**

A model trained in one district does not automatically work in another. Soils, irrigation, varieties and sowing dates all differ. Figure 2 brings together the accuracy figures cited in this article. They range from about 75 to 96 per cent, but they also measure different things, so a result reported for one study area should not be assumed to hold elsewhere without local testing.

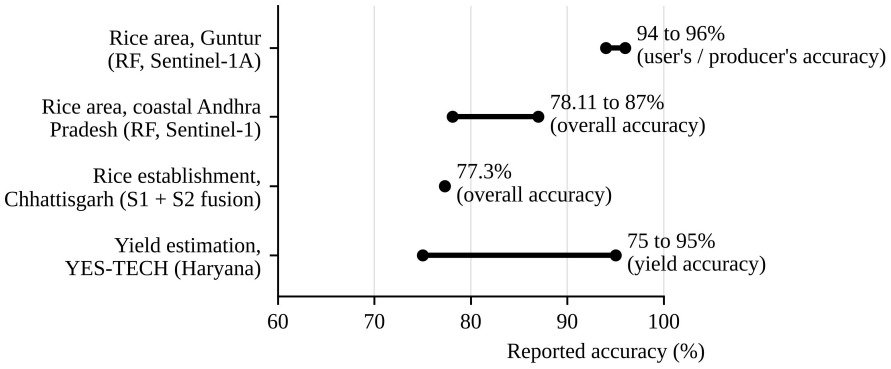



***Figure 2. Reported accuracy of GeoAI applications in India (Source: Compiled by the authors from references 2, 7, 11 and 13).***

**Interpretability**

Many machine learning models, deep learning models in particular, cannot easily explain how they reach a result. This matters most when predictions carry money. Under YES-TECH, insurance claims now depend partly on model-derived yields, and a farmer who disputes a claim needs an explanation, not just a number[6].

**The last-mile advisory gap**

The final limitation lies outside the model. Krishi-DSS is described as a base from which farmer advisories and early warnings for pests, heavy rain and hailstorms *can be developed*[9]. The data exists, but turning it into timely advice in the farmer's own language remains a separate task.

**The Road Ahead**

Four elements, working together, could carry the loop from government systems to the field (Figure 3).

**Open geospatial data:** wider access to ground-truth libraries such as that of Krishi-DSS, collected to common standards, would let researchers test models across regions. *Local validation:* before a model is used for decisions that carry money, it should be tested against field data from the district where it will run, with published accuracy figures and independent audits. *Extension workers:* extension staff can explain advisories and insurance assessments in local terms, and their geotagged field records become new ground truth, so every field visit also improves the model. *Accessible tools:* advice must reach farmers in their own language, through mobile apps, SMS or voice messages, early enough to act on.

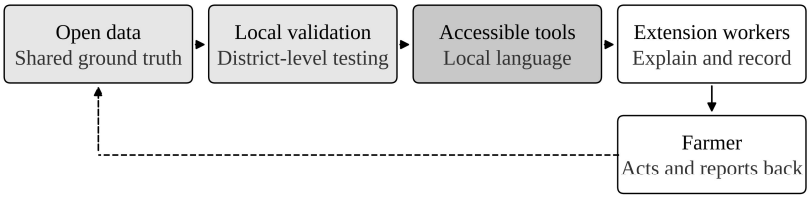



***Figure 3. A framework for extending the GIS–AI loop to the farm (Source: Authors' illustration)***

**Conclusion**

This article began with the difference between knowing where a crop grows and anticipating how it will perform. Satellite remote sensing, GIS and machine learning have made the second possible at national scale, as FASAL, NADAMS, YES-TECH and Krishi-DSS show. This review has set those achievements against their limits: patchy ground truth, uneven accuracy across regions, opaque models and advice that does not always reach the farm. Future applications will depend less on new satellites than on shared data, local testing and people who can carry results to the field. When those pieces come together, the agricultural map will serve everyone who works the land.

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# GREEN GOLD: HOW INDIA'S FARMERS CAN TURN CARBON INTO CURRENCY

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**Abstract**
Climate change threatens Indian agriculture, yet farming also emits methane, nitrous oxide and carbon dioxide. Carbon credits, each representing one tonne of $CO_2$-equivalent avoided or removed, can give farmers a new income stream. This article summarises climate impacts on Indian crops, the Paris Agreement and Article 6 market framework, major certifiers and methodologies (Verra VM0042, VM0051, VM0044, Gold Standard), India's Carbon Credit Trading Scheme (CCTS), prices, ongoing projects, government support and key challenges. It concludes with a practical, step-by-step pathway for farmers to participate and earn.

**Keywords:** Carbon credits, Carbon farming, Climate-smart agriculture, CCTS, Soil organic carbon

## Introduction

Climate change is a daily reality for the roughly 700 million Indians who depend on agriculture. Erratic monsoons, droughts, hailstorms and heat waves now routinely disrupt the farming calendar. At the same time, agriculture contributes to emissions through methane from flooded paddies and livestock, nitrous oxide from excess fertiliser, and $CO_2$ released by tillage and residue burning. Farming is thus both a victim and a contributor. This duality creates an opportunity. Practices such as changed tillage, paddy water management, residue management and boundary tree planting can generate verifiable reductions or removals of greenhouse gases. Measured in tonnes of $CO_2$ equivalent ($tCO_2e$), these become tradable carbon credits that corporations with net-zero pledges are willing to buy, offering income to the farmers most exposed to climate risk.

## Climate Change and Indian Agriculture

The IPCC identifies agriculture as highly vulnerable; global productivity could fall by nearly 16% by the 2080s, and by almost 20% in developing countries. India's diverse agro-climatic zones are especially exposed. A study of twenty crops across twenty states (1966–2016) found that rising temperatures and shifting rainfall are already compressing yields, and district-level projections for 2021–2050 and 2071–2098 show declines for most major food crops (SAGE Journals, 2026). Rice yields could fall by 3–22% by 2100 depending on emission pathways (Springer Nature, 2024). Because over half of India's rural workforce depends on farming, such losses affect rural incomes, food security and nutrition, and burden small and marginal farmers most. This vulnerability has

pushed policymakers towards market mechanisms that reward climate-resilient, low-emission practices.

**Global Framework for Carbon Markets**

**Paris Agreement and Article 6.** The 2015 Paris Agreement commits nearly 200 countries to hold warming well below 2°C, pursuing 1.5°C, through Nationally Determined Contributions (NDCs). Article 6 enables cooperation through carbon markets: Article 6.2 governs transfers between countries (ITMOs), Article 6.4 creates the UN Paris Agreement Crediting Mechanism (PACM), successor to the Clean Development Mechanism, and Article 6.8 covers non-market cooperation (UNFCCC). In February 2026 the PACM approved its first credit issuance, for a clean-cooking project in Myanmar, with reductions about 40% lower than under the old CDM owing to stricter baselines (ESG News, 2026).

**COP30.** COP30 (Belém, November 2025) adopted the 'Belém Political Package' strengthening adaptation finance, just transition and accountability, and a declaration on hunger and poverty backed by 43 countries and the EU, plus US$1.8 billion for indigenous land rights for 2026–2030. For India, global finance and market rules will shape support reaching its agrarian economy (Down To Earth, 2026).

**Key institutions.** The UNFCCC oversees the PACM. Verra runs the Verified Carbon Standard (over 4,000 projects in 95 countries) and publishes agricultural methodologies. Gold Standard certifies projects alongside the UN Sustainable Development Goals. The Integrity Council for the Voluntary Carbon Market (ICVCM) awards its Core Carbon Principles label; in October 2025 it approved the first agricultural methodologies, Verra's VM0042 and the American Carbon Registry's Soil Enrichment Protocol (ICVCM, 2025). In India, the Bureau of Energy Efficiency (BEE) administers the CCTS (ICAP).

**Carbon Credits and How Agriculture Generates Them**

A carbon credit is one tonne of $CO_2e$ prevented or removed, verified against an approved methodology and registered so it cannot be sold twice. Compliance markets (e.g., EU ETS, India's CCTS) are legally mandated, whereas voluntary markets serve self-declared net-zero goals. Every credit must show additionality, permanence, measurability, no leakage and no double counting.

Farms generate credits by cutting emissions or by storing carbon in soil and biomass. Verra's VM0042 (Improved Agricultural Land Management, v2.2) credits reduced tillage, cover cropping, rotation, residue, fertiliser and grazing management, requiring baselines from soil sampling or calibrated modelling plus independent verification (Verra); in 2025 it became one of the first two agricultural methodologies to receive the ICVCM label. VM0051 targets rice methane through alternate wetting and drying, shorter flooding and direct seeding, requiring at least a 5% emission cut and proof of additionality; Gold Standard has a parallel rice methodology. VM0044 certifies biochar, which can lock carbon in soil for centuries. Agroforestry on boundaries or degraded land builds long-term carbon sinks, and is among the highest-value credit categories in India. Table 1 summarises common practices.

Table 1. Common practices that generate agricultural carbon credits

| Practice | Primary GHG effect | Typical methodology |
|---|---|---|
| Reduced/zero tillage | Increases soil organic carbon | Verra VM0042 |
| Cover cropping and crop rotation | Builds soil carbon, reduces erosion | Verra VM0042 |

| Practice | Primary GHG effect | Typical methodology |
|---|---|---|
| Alternate wetting and drying in paddy | Cuts methane from rice | Verra VM0051/Gold Standard |
| No residue burning | Avoids CO2 and black carbon | Verra VM0042 |
| Biochar application | Long-duration carbon removal | Verra VM0044 |
| Agroforestry/boundary trees | Carbon sequestration in biomass | REDD+-aligned/ARR |
| Optimised nitrogen use | Reduces nitrous oxide | Verra VM0042 |
| Improved grazing/pasture management | Enhances soil carbon, reduces methane | Verra VM0042 |

**Carbon Credits in India: Policy and Prices**

India's CCTS derives from the Energy Conservation (Amendment) Act, 2022, was notified in June 2023, and is run by BEE under the National Steering Committee for the Indian Carbon Market. Regulations of July 2024 set up an intensity-based baseline-and-credit system covering about 740 entities in eight industrial sectors such as cement, steel and aluminium. The Indian Carbon Market Portal launched in March 2026 (Khaitan Legal, 2026). A voluntary Offset Mechanism, open from June 2025 to agriculture, forestry and MSMEs, is being operationalised, with agriculture methodologies expected to adapt CDM, Gold Standard and Verra frameworks (ICAP). The EU's Carbon Border Adjustment Mechanism gives India a trade incentive for domestic carbon pricing, and the UK recognised the CCTS under its own CBAM in September 2026.

Prices remain fragmented. Voluntary credits averaged about Rs 194 per tonne $CO_2$ in early 2024; in 2026 estimates range from Rs 200–400 for lower-quality credits to Rs 1,400–2,800 for high-integrity agroforestry projects. Compliance certificates may trade at Rs 250–2,000 per tonne, while agricultural soil-carbon projects such as Grow Indigo's reference international benchmarks of US$40–60 (The Federal, 2026). The World Economic Forum warns that the CCTS needs a price-stability mechanism to avoid the oversupply and price collapse seen in Alberta and Australia (WEF, 2025).

**Projects and Schemes on the Ground**

Boomitra's URVARA project, using satellite imagery and AI to estimate soil carbon, had its first Indian issuance in April 2025, verifying 47,311 credits with about 315,735 more expected over 20 years; it involves over 12,000 smallholders across nearly 50,000 acres in six states (Boomitra, 2025). Varaha had onboarded over 80,000 farmers on about 700,000 acres, with offtake agreements including Google. Grow Indigo's 'Adi' project helps Punjab and Haryana farmers shift to direct-seeded rice, with a first issuance of over 50,000 credits from about 30,000 acres (The Federal, 2026).

The Union Budget 2026–27 announced a Rs 20,000 crore CCUS support programme that for the first time brings farmers into the carbon market through FPOs, cooperatives or aggregators, which handle paperwork and audits (The Better India, 2026). NABARD has begun outreach, including a pilot with about 3,500 mango farmers in Koppal, Karnataka, though farmer groups report unclear information (The Quint, 2026). The National Mission on Natural Farming (Rs 2,481 crore, approved November 2024) targets one crore farmers, 7.5 lakh hectares, 10,000 Bio-Input Resource Centres, Rs 4,000 per acre per year for two years and over 70,000 Krishi Sakhis; it is not a carbon scheme but promotes practices overlapping with VM0042 (PIB).

**Challenges**

Key concerns include: (i) low farmer awareness of contract terms, income calculation and duration; (ii) aggregator costs that reduce farmers' share; (iii) costly soil sampling, with satellite/AI monitoring still being tested against ICVCM standards; (iv) price volatility and no domestic benchmark for soil-carbon credits; (v) greenwashing risk, as some cookstove and afforestation projects have faced credibility questions; (vi) single-species plantations that favour carbon over biodiversity; and (vii) 10–20-year contracts that interact uneasily with tenancy, leasing and inheritance (The Quint, 2026).

**How a Farmer Can Earn from Carbon Credits**

Farmers generally participate through an intermediary such as an FPO, cooperative, agri-tech firm or NGO. The process is: (1) join a registered project (e.g., Boomitra, Varaha, Grow Indigo); (2) adopt eligible practices such as reduced tillage, cover cropping, alternate wetting and drying, residue retention or boundary trees; (3) establish a baseline and monitor using satellite data, soil sampling or mobile apps; (4) obtain independent third-party verification; (5) receive credits issued by Verra, Gold Standard or the CCTS registry; and (6) share in sale proceeds, usually per acre or per tonne. Industry estimates suggest additional income of about Rs 5,000–50,000 per hectare per year when carbon revenue, input savings and yield gains are combined. Farmers should verify accreditation (Verra, Gold Standard or BEE), understand the commitment length, ask how revenue is shared, and treat carbon income as a supplement to sound crop planning.

**Conclusion**

India combines millions of small farm households, wide agro-ecological diversity and visible climate stress, making it a major potential source of high-integrity agricultural carbon credits. Building blocks are falling into place: the CCTS, a professionalising agri-tech ecosystem, recognition by trading partners such as the UK, and budgetary support through the CCUS programme and natural farming mission. The remaining task is to ensure value reaches the farmer transparently and fairly, through farmer education, cheaper satellite- and AI-based monitoring, a credible domestic price benchmark and vigilance against greenwashing. If achieved, carbon credits can turn soil threatened by climate change into a source of climate-resilient income.

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# GREENING THE URBAN LANDSCAPE: THE ROLE OF FLORICULTURE AND ORNAMENTAL PLANTS

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**Abstract**

Rapid urbanisation has increased environmental challenges such as urban heat, declining vegetation cover, habitat fragmentation and pressure on natural resources. Floriculture and ornamental horticulture can contribute to greener and more resilient cities by integrating flowering plants, trees, shrubs, climbers, grasses and foliage plants into parks, roadsides, rooftops and other urban spaces. Beyond beautification, ornamental plants provide ecosystem services including microclimate regulation, stormwater management, biodiversity support and resources for pollinators. Sustainable plant selection based on climate adaptability, water requirements, heat and drought tolerance, soil conditions and ecological compatibility is essential for long-term landscape performance. Efficient irrigation, mulching, soil-health management and biodiversity-friendly practices can further improve sustainability. Integrating floriculture with urban green infrastructure can therefore create attractive, functional and climate-resilient landscapes that enhance environmental quality and urban well-being.

## Introduction

Rapid urbanisation is progressively transforming natural and semi-natural areas into built environments. The expansion of impervious surfaces, increasing urban temperatures, habitat fragmentation and declining vegetation cover are creating significant environmental challenges for cities. In this context, urban greenery is increasingly recognised as an important component of sustainable urban development and climate adaptation. Floriculture and ornamental horticulture can contribute to this transition by integrating flowering plants, ornamental trees, shrubs, climbers, grasses and foliage plants into parks, roadsides, residential areas, institutional landscapes, rooftops and other urban spaces. Beyond their aesthetic function, these plants can provide ecosystem services, support urban biodiversity and contribute to the development of multifunctional green infrastructure.

## Urban Floriculture and the Need for Greener Cities

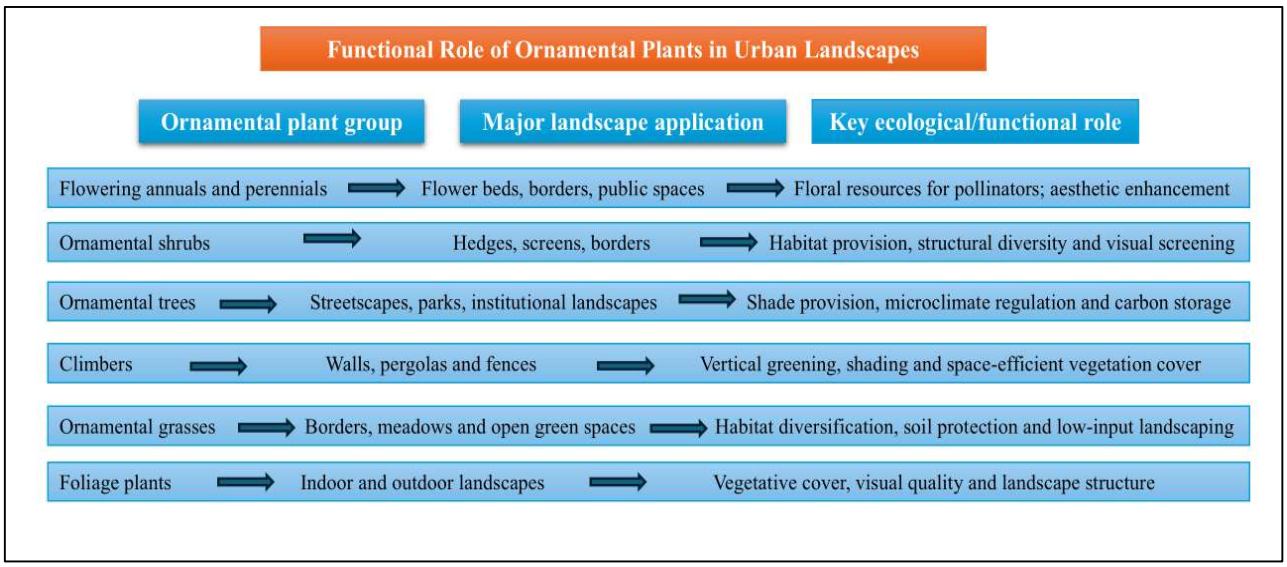
Urban floriculture is evolving from a primarily aesthetic activity into an important component of urban ecological management. Vegetated spaces can help moderate local microclimatic conditions, improve the visual and ecological quality of built environments and provide habitat and foraging resources for urban biodiversity. The increasing frequency and intensity of extreme heat events makes the selection of resilient ornamental plants particularly important. Recent research on urban ornamental plants in urban environment highlights the significance of heat tolerance and physiological resilience for maintaining functional green spaces under changing climatic conditions. Thus, the incorporation of floricultural plants into urban planning can contribute to both environmental quality and landscape functionality.

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| Conventional Urban Landscaping | Sustainable Urban Landscaping |
|---|---|
| Primarily aesthetic design | Multifunctional ecological design |
| High-maintenance plant selections | Resource-efficient plant selections |
| Limited species diversity | Greater plant and structural diversity |
| High irrigation demand | Water-use-efficient species and irrigation |
| Intensive chemical management | Integrated pest management (IPM) |
| Highly manicured lawns | Diverse lawns, meadows and habitat plantings |
| Isolated planting areas | Connected urban green infrastructure |
| Short-term visual objectives | Long-term ecological and climate resilience |

**Role of Ornamental Plants in Urban Landscapes**

Ornamental plants provide colour, form, texture, seasonal variation and spatial structure to urban landscapes. Annuals, perennials, shrubs, trees, climbers, bulbs and ornamental grasses can be combined according to site conditions and landscape objectives. However, scientific plant selection should extend beyond their ornamental characteristics. Important criteria include water requirements, thermal tolerance, growth habit, flowering phenology, soil adaptability, canopy characteristics, maintenance requirements and ecological compatibility. Flowering ornamental plants can also provide floral resources for pollinators and other beneficial organisms. Research indicates that appropriately selected ornamental plants can contribute to urban biodiversity and ecosystem services, particularly when invasive species are avoided and sustainable maintenance practices are adopted. Consequently, ornamental plants can perform aesthetic, ecological and functional roles simultaneously.



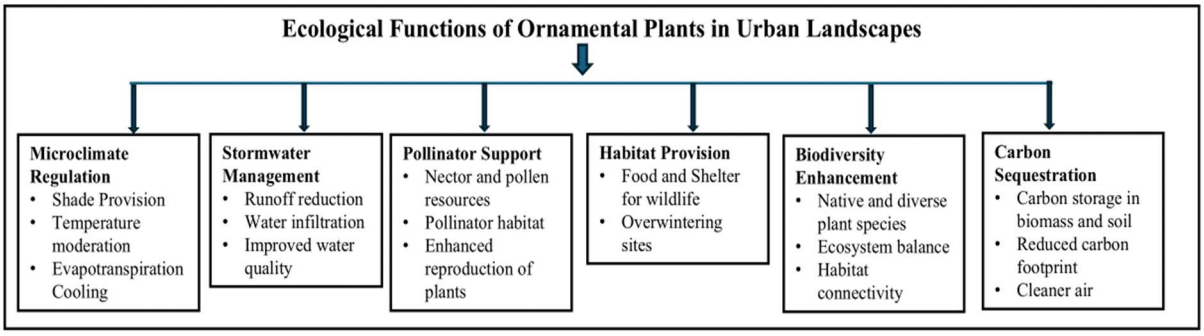

**Landscape Plants as Urban Green Infrastructure**

The concept of urban green infrastructure represents a shift from viewing vegetation primarily as decoration to recognising it as functional infrastructure. Parks, green belts, roadside plantations, green roofs, vertical gardens and other vegetated areas can collectively form networks of green spaces within the urban matrix. Such infrastructure can provide multiple regulating, supporting and

cultural ecosystem services, including microclimate regulation, stormwater management, biodiversity support, recreational opportunities and benefits to human well-being. Systematic reviews demonstrates that the type, structure, connectivity and management of urban vegetation plays major role in influencing the ecosystem services provided by green infrastructure. Therefore, landscape design increasingly needs to consider ecological performance alongside visual quality.

**Environmental and Ecological Benefits**

Urban vegetation can influence several environmental processes. Trees and other plants provide shade and contribute to evapotranspiration, thereby helping regulate local thermal conditions. Vegetated surfaces can also intercept rainfall and contribute to stormwater regulation. Ornamental landscapes can provide additional ecological value when they contain a diversity of flowering species. Diverse plant communities can provide nectar, pollen, shelter and other resources for pollinators and associated fauna. Research on ornamental plants has shown that their contribution to urban biodiversity depends strongly on species selection, plant diversity and management practices. Non-invasive ornamental species with suitable ecological characteristics can therefore contribute to biodiversity while maintaining landscape aesthetics. The objective should therefore be to develop landscapes that provide multiple ecosystem services rather than focusing solely on visual appearance.




**Sustainable Plant Selection and Landscape Management**

The principle of “right plant, right place” is fundamental to sustainable landscape horticulture. Plant material should be selected according to climatic conditions, soil properties, water availability, sunlight exposure and anticipated maintenance requirements. Climate change is making this principle increasingly important. Heat waves, drought and other abiotic stresses can affect plant growth, flowering, physiological performance and landscape longevity. Recent scientific research is consequently focusing on heat-tolerant and drought-resilient ornamental plants for future urban landscapes.

The use of locally adapted and ecologically appropriate plant material can reduce maintenance requirements and improve landscape resilience. Sustainable practices such as efficient irrigation, mulching, soil-health management, integrated pest management and appropriate pruning can further reduce resource consumption. Plant selection should also consider potential ecological risks, particularly those associated with the introduction of invasive species. Therefore, ornamental value should be balanced with ecological compatibility and long-term landscape performance.

**Future Prospects of Urban Floriculture**

The future of urban floriculture is likely to be shaped by climate-resilient plant material, smart horticultural technologies and nature-based landscape design.

Plant breeding and physiological screening can help identify ornamental genotypes with greater tolerance to heat, drought and other environmental stresses. At the landscape level, smart irrigation systems, soil-moisture sensors and digital monitoring can improve water-use efficiency and plant management. There is also growing interest in multifunctional landscapes incorporating flowering meadows, native and adapted plants, green roofs, vertical gardens and biodiversity-friendly planting schemes. Such approaches can combine ornamental value with habitat creation and ecosystem-service delivery. This represents a transition from conventional ornamental landscaping towards more ecologically functional forms of urban horticulture.

**Conclusion: Towards Greener and Resilient Cities**

Floriculture and ornamental plants can make an important contribution to the ecological transformation of urban environments. Their value extends beyond beautification to include biodiversity support, microclimate regulation, ecosystem-service provision and enhancement of human well-being. The future of urban landscapes will increasingly depend on scientifically informed plant selection, greater plant diversity, efficient resource management and climate-responsive design. Integrating floriculture with urban green infrastructure can therefore help create landscapes that are not only attractive, but also ecologically functional, climate-resilient and sustainable. In this way, ornamental plants can become an integral component of the transition towards greener and more resilient cities.

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# FROM FARM TO FORK: HOW FOOD TRACEABILITY BUILDS TRUST IN EVERY BITE

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A simple guide to the journey of Ramnad Mundu chilli
Farm → Harvest → Transport → Kitchen → Fork
Fresh from farm to fork.
Ramnad Mundu chilli: a GI-tagged crop associated with Ramanathapuram district.

## Introduction

When we buy food, we usually see only the final product. Behind that product is a much longer journey from the land where it was grown, to harvesting, drying or grading, storage, transport, and finally the buyer or market.

Food traceability means keeping a clear record of that journey. It helps answer simple but important questions: Where was the produce grown? Which part of the farm did it come from? When was it harvested? What happened to it after harvest? And can the information be checked when it is needed?

FoodTraze's approach takes traceability down to the farm-block level. Using Hyperledger Fabric, the platform connects the exact growing block with crop information, inputs, individual harvest events, and later stages of the supply chain.

## Why Traceability Matters

- It helps verify the origin of produce, especially for GI-tagged and premium crops.
- It creates records of inputs and spray activity that can support export and certification requirements.
- It can distinguish produce from different blocks on the same farm.
- It records separate picking rounds when a crop is harvested several times in one season.
- It gives buyers and certification bodies a connected record instead of relying only on paper or memory.

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**The Farm-to-Fork Journey**

Traceability can be understood as a story that follows a batch of food from its point of origin to its destination. For agriculture, the story can begin with a specific farm block.

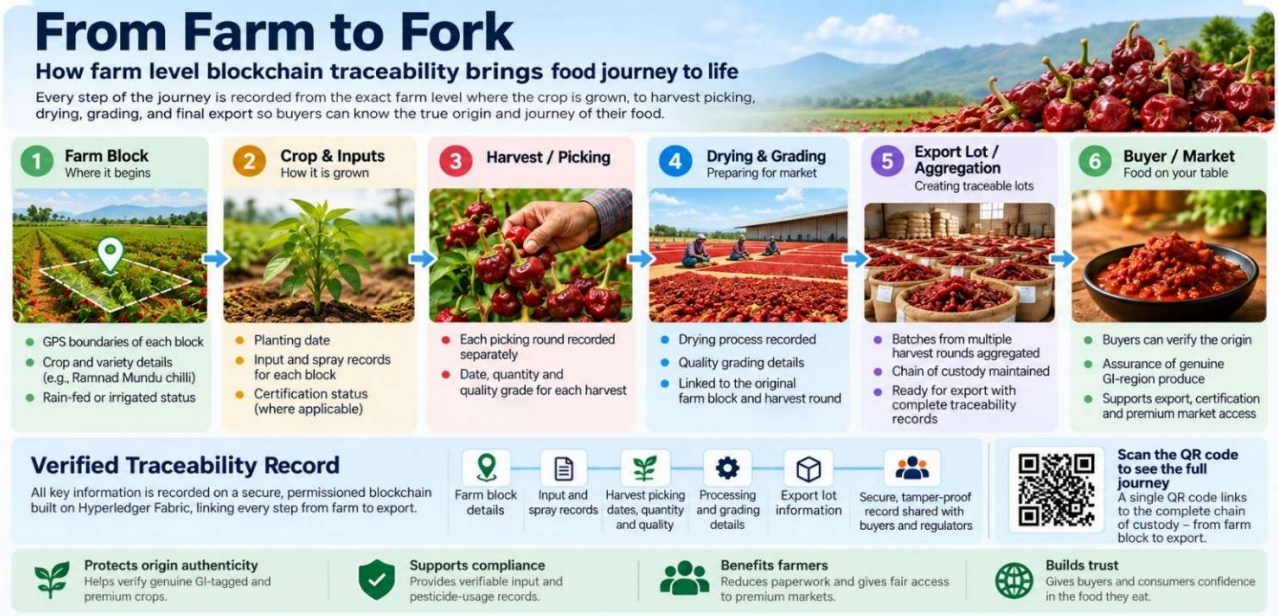



***Illustration: a simplified farm-to-fork traceability journey.***

**1. Farm and Block**

The journey starts by identifying the farm and, more importantly, the individual block where the crop is grown. The platform can record block boundaries, crop and variety, production status, and relevant certification information.

**2. Crop and Inputs**

Information about planting, inputs, and spray records can be linked to the particular block. This matters because two blocks on the same farm may have different production histories.

**3. Harvest and Picking**

Every picking event can be recorded as its own event, with its date, quantity and quality grade.

**4. Drying, Grading and Export**

After harvesting, produce can move through drying and grading before being combined into an export lot. The traceability record keeps these stages connected to the original block and harvest information.

**5. QR Code and Chain of Custody**

A single QR code can connect to the relevant chain-of-custody information, allowing authorized users to trace the product from the farm block through later stages such as drying, grading, and export-lot aggregation.

**Ramnad Mundu Chilli: A Real-World Example**

Ramanathapuram, or Ramnad, Mundu chilli is a round, thick-skinned chilli variety grown mainly across five taluks of Ramanathapuram district: Tiruvadanai, Mudukulathur, Kadaladi, RS Mangalam and Kamuthi. It received its GI tag in 2023. The crop is mainly cultivated as a rain-fed crop by dryland smallholder farmers.

FoodTraze partnered with TNAPEx to bring farm-level blockchain traceability to around 100 Mundu chilli farmers in Kamudhi village. The system records block-level information and links it to the crop's production and harvest history.

**What Gets Recorded?**

- GPS boundaries of the farm block, helping confirm that produce came from the relevant GI-registered area.
- Rain-fed or irrigated status and input or spray records for the block.
- Each of the season's three to four picking rounds as a separate traceable event.
- Date, quantity, and quality grade for each harvest event.
- The chain of custody through drying, grading, and export-lot aggregation.

**Why This Is Useful**

For exporters and certification bodies, clear records can help address questions around origin and pesticide-related documentation. For farmers, block-level records can help demonstrate which produce came from which production area. For buyers, the system provides a more detailed record of what they are purchasing.

**The Role of Blockchain**

FoodTraze uses Hyperledger Fabric, a permissioned enterprise blockchain framework. The source documents describe it as providing an auditable history, controlled access to sensitive information, support for multiple harvest events, and selective sharing of records with buyers, auditors and other authorized participants.

**How FoodTraze Helps Make Produce Export-Ready**

For export markets, producing good-quality food is only part of the journey. Exporters also need clear, verifiable documentation about where the produce came from, how it was produced, and how it moved through the supply chain. Food Traze helps make export-ready by connecting farm-block information, GPS-based origin records, input and spray records, individual harvest details, quality grades, and the chain of custody through drying, grading and export-lot aggregation. This gives exporters and certification bodies a connected digital record that can support origin verification, pesticide-compliance documentation, and other export requirements. In simple terms, FoodTraze helps turn farm records into evidence that can travel with the product to the export market.

**Simple Conclusion: From Claim to Evidence**

Food traceability is ultimately about trust. A label can tell us where a product is supposed to come from, but traceability creates a connected record that can help show where it came from and what happened along the way.

From farm block to harvest, from harvest to drying and grading, and from there to the buyer, each step can become part of one clear story. For crops such as Ramnad Mundu chilli, this can support origin verification, documentation, certification and access to premium markets.

In simple words: Farm-to-Fork traceability means knowing the journey of our food and being able to show that journey when it matters.

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# HYPERCONNECTED FAMILY: HOW DIGITAL FRICTION RESHAPES LIFESPAN DEVELOPMENT AND QUALITY OF LIFE

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**Abstract**

Digital technology has redefined global communication, career flexibility and daily social networking, providing unprecedented access to information. However, this unyielding connectivity has simultaneously introduced chronic psychological friction, often referred to as digital stress. Grounded in a systemic lifespan and ecological perspective, this article conceptualizes digital stress not merely as an isolated individual inconvenience, but as a dynamic phenomenon that disrupts developmental trajectories, compromises family functioning and erodes personal well-being. By integrating contemporary literature, empirical data and recent institutional policy warnings—including reports from the World Health Organization (WHO), the American Psychological Association (APA) and national economic surveys—we examine core behavioral constructs such as technostress, techno-invasion, phubbing, the fear of missing out (FoMO), the joy of missing out (JoMO) and problematic social media use. Finally, actionable, multi-level interventions are proposed, ranging from individual digital hygiene and family media agreements to organizational right-to-disconnect frameworks, with the aim of restoring relational balance in the modern home.

**Keywords:** Digital stress, Technostress, Family systems, Problematic social media use, Quality of life.

## Introduction

In the contemporary socio-technical ecosystem, human beings exist within an unprecedented environment of perpetual, around-the-clock connectivity. While digital tools, mobile communication networks and social platforms have fundamentally revolutionized education, professional workflows and global linkage, they have simultaneously imposed profound psychological and biological demands on human adaptation. For students navigating formative years, working adults juggling demanding careers and parents striving to maintain household harmony, the traditional boundary separating online presence from offline domestic life has grown increasingly porous and fragile.

From a systemic ecological perspective, individual growth and well-being do not occur in an isolated vacuum. Grounded in Bronfenbrenner's Ecological Systems Framework, an individual's lifelong

developmental outcomes are shaped by continuous, reciprocal interactions within their immediate micro-environments—such as the family unit, peer groups, educational classrooms and occupational workplaces—as well as the broader socio-cultural macrosystem (Gandarillas *et al*., 2024). When digital devices, notification pings and algorithmic feeds penetrate these immediate microsystems, they introduce unique structural stressors. Over time, these digital intrusions can subtly alter emotional attunement, disrupt identity formation and self-esteem in youth, blur occupational-domestic boundaries for working adults and compromise the overarching interpersonal relationship quality across the entire lifespan (Carlotto *et al*., 2017; Harunavamwe and Ward, 2022).

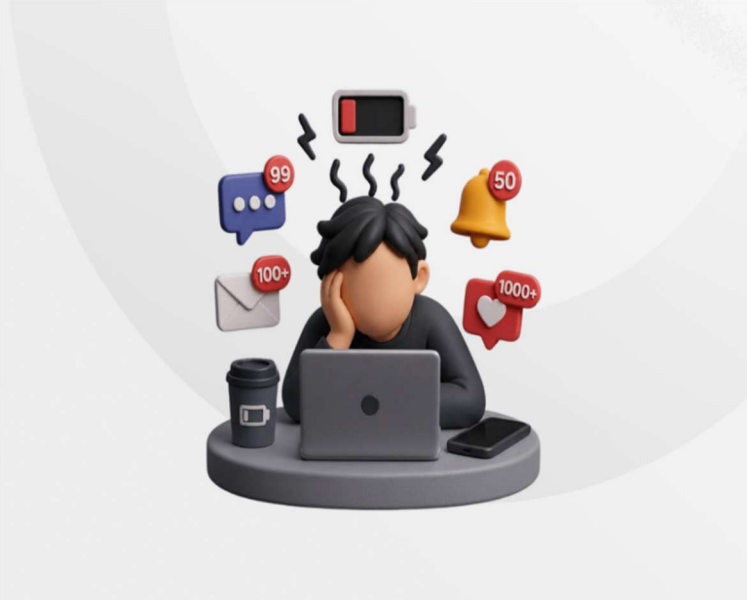
Furthermore, the scale of this behavioral shift has drawn intense scrutiny from global health and policy institutions. International public health findings highlight a marked escalation in problematic digital behaviors among younger demographics, revealing that screen-centric lifestyles are no longer just a matter of lifestyle preference, but a pressing public health challenge (World Health Organization Regional Office for Europe [WHO/Europe], 2024; Press Information Bureau [PIB India], 2026). Understanding how this digital friction operates across the lifespan requires a rigorous examination of core technological constructs, physiological impacts and evidence-based countermeasures designed to safeguard human flourishing.

**Mapping the Lexicon of Digital Stress**

Understanding digital stress requires establishing clear conceptual definitions. In behavioral literature and occupational health research, several core constructs describe the modern human interaction with technology:

- **Digital Stress:** The subjective experience of psychological strain, anxiety, or cognitive overload resulting from continuous engagement with digital technologies and communication platforms (Zhan *et al*., 2025).
- **Technostress:** A specialized form of stress experienced when individuals are unable to adapt to or cope with information and communication technologies (ICTs) in a healthy manner, encompassing techno-overload, techno-invasion and techno-complexity (Carlotto *et al*., 2017).
- **Techno-Invasion:** The intrusive blur between work or school and personal life, where digital devices enable constant reachability outside formal operating hours, invading domestic and leisure domains (Harunavamwe and Ward, 2022).
- **Fear of Missing Out (FoMO):** A pervasive anxiety driven by the belief that others are having rewarding social experiences from which one is excluded, leading to compulsive digital checking behaviors (Gupta and Sharma, 2021).
- **Joy of Missing Out (JoMO):** A psychological state of contentment and liberation derived from voluntarily disconnecting from digital stimuli, appreciating the present moment and prioritizing inner peace over digital hyper-vigilance (Gupta and Sharma, 2021).
- **Phubbing (Phone Snubbing):** The practice of ignoring or snubbing physically present individuals in social or family settings in favor of paying attention to a smartphone, which erodes conversational trust and relational intimacy.
- **Problematic Social Media Use (PSMU):** A behavioral pattern characterized by diminished control over engagement, withdrawal symptoms when offline and the neglect of everyday responsibilities and offline activities (Amirthalingam and Khera, 2024).

- **Continuous Partial Attention:** The habitual division of cognitive processing across multiple digital stimuli, preventing deep focus and draining mental stamina.
- **Nomophobia:** An abbreviation for *"NO Mobile PHOne PhoBIA"*—the irrational fear, apprehension, or discomfort experienced when an individual is separated from their mobile device or disconnected from digital networks.




**Source: https://share.google/kRaGqh9LopfJaNyUs**

**Lifespan and Family Dynamics: A Systems Perspective**

Human development is dynamic and cumulative. Digital stress manifests differently depending on an individual's life stage and family context.

**Childhood and Adolescence**

Adolescence is a critical developmental stage characterized by identity exploration, heightening peer sensitivity and ongoing executive function maturation. Digital platforms exacerbate approval anxiety and online vigilance, where teens feel pressured to respond instantly to peer interactions and maintain a curated online persona (American Psychological Association [APA], 2023). Cross-national data from the World Health Organization highlight a sharp rise in problematic social media use among adolescents, climbing from 7% in 2018 to 11% in 2022, with over a third maintaining continuous online contact with friends (WHO/Europe, 2024). While digital tools foster community, chronic exposure to online hostility and cyberbullying correlates strongly with generalized anxiety, low self-esteem and social isolation (Gandarillas *et al*., 2024).

**Adulthood and Family Systems**

For working adults and caregivers, digital stress often takes the form of techno-invasion. The inability to psychologically detach from workplace messaging apps or social obligations creates work-family conflict, a state in which occupational role demands spill over into domestic life (Harunavamwe and Ward, 2022). Furthermore, when parents experience digital overload, they may engage in phubbing or "technoference"—interrupting face-to-face exchanges with children or partners to check notifications (Carlotto *et al*., 2017). This subtle withdrawal of attention can diminish emotional responsiveness, increase marital conflict and alter early parent-child attachment dynamics.

**Physiological and Psychological Toll on Quality of Life**

The human body and mind evolved for intermittent physical stimuli rather than continuous digital hyper-arousal. The chronic activation of stress response systems via digital triggers has tangible consequences across physical, psychological and social dimensions:

**Physiological Strain and Sleep Disruption:** Screen exposure before bed suppresses nocturnal melatonin synthesis due to short-wavelength blue light. Moreover, cognitive hyper-arousal caused by late-night checking impairs sleep architecture, leading to chronic fatigue and insomnia (Patel *et al*., 2025). Continuous notification alerts trigger micro-doses of cortisol and adrenaline, elevating resting heart rates and contributing to musculoskeletal issues such as forward head posture and ocular strain like dry eye disease.

**Psychological and Emotional Depletion:** Continuous processing of fragmented digital incoming data leads to cognitive burnout, reduced attention spans and lower emotional resilience. However, robust research indicates that strong offline social support serves as a powerful buffer, significantly moderating the negative impacts of technostress on personal life satisfaction (Mehmood *et al*., 2024). Furthermore, thoughtful digital communication practices can help leverage online spaces for peer support and mental health literacy without triggering cognitive fatigue (Naslund *et al*., 2020).

**Official Survey Findings and Public Policy Insights**

Global institutional bodies and government economic surveys increasingly recognize digital overuse as a critical data-backed policy issue:

**Pew Research Centre:** National surveys reveal that 72% of teenagers report feeling peaceful when they are away from smartphones, yet 44% report experiencing anxiety when disconnected (Pew Research Centre, 2024). Additionally, 81% of teens and 69% of adults actively use social platforms, exposing a large demographic to constant social evaluation and connection overload.

**Government Economic and Public Policy Reports:** Recent official economic and policy documents—such as national surveys addressing digital addiction—have drawn attention to the scale of screen consumption among youth aged 15–29, who enjoy near-universal digital access (PIB India, 2026). These reports highlight profound impacts on academic performance, cognitive development, workplace productivity and financial vulnerability due to compulsive online gaming, gambling and social media scrolling. In response, regulatory bodies have intensified online safety frameworks, age-gating protocols and nationwide cyber-awareness campaigns.

**Innovative Strategies to Manage and Cure Digital Stress**

To effectively counteract digital fatigue and restore cognitive harmony, modern behavioural frameworks propose the following innovative solutions:

**Grayscale Reversal and Device Docking ("The Digital Fast")**

To counter persuasive app design that triggers dopamine loops, users can permanently switch smartphone screens to monochrome (grayscale). Stripping away vibrant colour aesthetics significantly lowers the psychological reward of mindless scrolling. Additionally, deploying a physical "Landing Pad" docking station outside the bedroom forces devices to remain out of reach overnight (Patel *et al*., 2025).

**The 20-20-20 Ocular Reset Rule**

To combat digital eye strain, fatigue and cognitive overload resulting from continuous screen exposure, individuals should practice the 20-20-20 rule: every 20 minutes spent looking at a screen,

a person must look at an object at least 20 feet away for at least 20 seconds. This physical break relaxes the ciliary eye muscles, reduces blink-rate deficits and provides a micro-pause for neurological recovery (Patel *et al*., 2025).

**Cultivating the Joy of Missing Out (JoMO)**

To actively counter the anxiety of FoMO, individuals can deliberately practice cultivating the Joy of Missing Out (JoMO). By reframing disconnection not as a social deficit, but as a deliberate reclamation of personal time and inner tranquility, individuals learn to embrace solitude, quite domestic spaces and offline hobbies without experiencing psychological distress (Gupta and Sharma, 2021).

**Gamified Family Analog Hours with Relational Stakes**

To eliminate phubbing during family time, households can establish a daily "Analog Hour" where phones are placed face-down in a communal lockbox. Incorporating light-hearted, game-like accountability penalties for early device retrieval turns digital boundary-setting into a shared, positive family ritual (Carlotto *et al*., 2017).

**Asynchronous Workplace Communication Charters**

To combat techno-invasion and work-family conflict, organizations can mandate "Async-First" operational charters. Setting explicit window expectations for after-hours emails (e.g., no required responses until the following morning) relieves the constant pressure of availability and protects domestic boundaries (Harunavamwe and Ward, 2022).

**Conclusion**

Digital stress is one of the defining psychological challenges of the modern era. Viewed through a systemic lifespan lens, the pervasive reach of technology influences far more than individual attention spans—it reshapes family dynamics, boundary management, emotional availability and developmental outcomes across generations. Recognizing the core drivers of technostress and nomophobia allows individuals and families to transition from passive consumption to intentional engagement. By establishing clear digital boundaries, protecting relational spaces and fostering supportive organizational policies, society can harness the advantages of innovation without sacrificing human health, family harmony and personal quality of life.

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# MAXIMIZING FARM PRODUCTIVITY AND PROFITABILITY THROUGH INTEGRATED FARMING SYSTEM MODELS; A PRACTICAL GUIDE FROM A SMALL HOLDER FARMER IN TELANGANA

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**Abstract**
Small and marginal farmers in rainfed regions face constant uncertainty due to their dependence on a single crop and erratic rainfall. This article presents a practical Integrated Farming System (IFS) model that combines farm pond–based aquaculture with poultry rearing to generate multiple sources of income from the same unit of land and water. Rainwater is harvested in ponds of 100–300 cubic meters and stocked with Indian major carps at a density of up to 2,500 fingerlings per acre. Poultry is integrated through over-pond sheds, floating cages, or bund-based units, which allow droppings to fertilize the pond directly. This practice reduces the cost of supplementary fish feed by 30–40%. The system produces fish, poultry meat, and eggs throughout the year, while nutrient-rich pond water enhances crop yields by 15–20%. Based on field experience, a one-acre unit can generate a net annual income exceeding Rs.2.3 lakh. This model improves resource-use efficiency, minimizes climate risk, and provides year-round livelihood security for small holders in semi-arid regions.

**Keywords:** Integrated Farming System, Farm Pond, Fish-poultry integration, Rainfed agriculture, Farm profitability, Resource recycling, small holder farmers, Telangana

**Introduction:** Many changes are happening in traditional agriculture day by day. Farmers are taking steps towards new machinery, use of technology, natural farming, use of organic fertilizers, and mixed farming. However, for the small and marginal farmers, governments are promoting an integrated agriculture system to promote agriculture and allied sectors. Even if there is a loss in agriculture, there is an opportunity to get income from other allied sectors. In order to effectively use the water available in rain-fed agricultural fields, fish in ponds and chickens and ducks can be raised in the integrated agriculture system and good income can be earned.

As a small farmer with two acres of dryland in Telangana, He previously depended solely on cotton or maize. If the monsoon failed, He had no income for the entire year. This is the reality for thousands of farmers in rainfed areas. They cannot sustain their families with one seasonal crop. However, He do have land, family labor, and rainwater that runs off every monsoon. An Integrated Farming System (IFS) allows us to use these resources effectively. IFS means linking crops, livestock, and fish so that the waste from one component becomes an input for another.

This low-cost IFS model that any small farmer can implement: a farm pond combined with fish and poultry. The system requires less water, reduces reliance on external feed, and provides income every month rather than once a year.

**Components of the IFS Model:**
**Farm Pond for Rainwater Harvesting** The first step is to construct a pond to collect rainwater. The size depends on the rainfall, slope, and catchment area. In our region, a pond with a capacity of

100–300 cubic meters is sufficient. Common dimensions range from 10 m x 10 m x 2.5 m to 15 m x 3.5 m, with side slopes of 1:5:1 to prevent soil erosion. A small silt trap is constructed on the upstream side to prevent the pond from filling with sediment. Inlet channels are provided to divert runoff into the pond.

The stored water serves three purposes: fish production, life-saving irrigation during dry spells, and drinking water for poultry and livestock.

**Fish Culture in the Pond** Once the pond fills during the monsoon, we apply 2 tonnes of well-decomposed cattle manure per acre one week before stocking. This promotes the growth of natural fish food. We stock fast-growing Indian major carps such as Catla (Catla catla), Rohu (Labeo rohita), and Common Carp (Cyprinus carpio). Fingerlings weighing 50–100 grams are stocked at a rate of 2,000 to 2,500 per acre.



Because the pond receives continuous fertilization from poultry, we do not need to purchase expensive commercial fish feed. The fish are ready for harvest in 8–10 months.

**Poultry Integration for Regular Income;** Poultry is the most important component of this system because poultry droppings are rich in nitrogen and phosphorus, which act as natural fertilizer for the pond. We use three practical methods:

**Over-pond Shed;** A bamboo or iron-framed shed with a slatted floor is constructed above the pond. It houses 100–200 country birds or broilers, and the droppings fall directly into the water.

**Floating Cages;** Cages measuring 8 ft x 5 ft x 4 ft are built with wooden frames and half-inch iron mesh. Plastic drums are tied beneath them for floatation. Each cage holds 20–25 birds. For a 1,000 sq.m pond, we install three to four cages. The cages are moved to a new location each week to distribute manure evenly.





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**Bunds-based System;** A small shed is built on the pond bund for poultry or ducks using the deep litter method. The used litter is later added to the pond.




With 200 birds, we can raise five batches of broilers each year, ensuring income every 45–60 days.



**Field Results and Benefits:**

**Reduced Costs and Improved Efficiency**: The integration of poultry and fish creates a self-sustaining system. Poultry manure eliminates 30–40% of the cost of supplementary fish feed. One pond can effectively support 2,000 fish and 200 poultry birds. If we increase the number of fish, we can proportionately increase the number of birds. No resource is wasted.

**Year-Round Income;** From one acre, the system provides the following returns:
1. Fish: 1,200 kg at Rs:120 per kg = Rs:1,44,000
2.Broiler meat: 1,800 kg at Rs:110 per kg = Rs:1,98,000
3. Additional income from eggs and improved crop yield using pond water = Rs:25,000

Total gross income = Rs:3,67,000. After deducting recurring costs of Rs:1,36,000 for chicks, fingerlings, and feed, the net annual profit is Rs:2,31,000.

Previously, cotton cultivation yielded only Rs: 40,000–50,000 per acre in a good year. The IFS provides four to five times higher income and ensures monthly cash flow.

**Climate Resilience;** During dry spells, pond water is used for one or two life-saving irrigations. Because this water is rich in organic nutrients, crop yields increase by 15–20% compared to crops irrigated with borewell water. Therefore, even if the monsoon fails, we do not face total crop loss.

**Employment Generation;** This system requires daily attention for feeding poultry, monitoring fish, and moving cages. It provides full-time employment for two to three family members and reduces the need for seasonal migration.

**Key Lessons for Farmers:**

| Recommended Practices | Practices to Avoid |
|---|---|
| Begin with a small pond of 10 m x 10 m if land is limited | Avoid overstocking fish without adequate poultry integration |
| Start with hardy country birds to reduce mortality | Do not allow pond water to remain unused; apply it to crops |
| Move floating cages weekly for uniform fertilization | Do not neglect poultry vaccination schedules |
| Maintain a pond depth of 2.5–3.5 m to minimize evaporation | Do not rely on external fish feed when poultry manure is available |

**Conclusion**

For small holders, the Integrated Farming System is not a complex technology but a logical use of available resources. By linking a farm pond with fish and poultry, we obtain fish, meat, eggs, and higher crop yields from the same unit of water. Production costs are low because each enterprise supports the other.

This model has transformed our livelihood. Instead of depending on one uncertain crop, we now have a steady monthly income. During drought years, the pond and poultry sustain our family. If every rainfed farmer adopts this system on even half an acre, agriculture can become both profitable and sustainable, encouraging rural youth to remain in farming.

We do not need large investments or advanced machinery. We only need to utilize our own resources to their full potential. This is the most practical way to maximize farm productivity and profitability.

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# INTEGRATED MANAGEMENT OF PESTS: A SUSTAINABLE APPROACH TO CROP PROTECTION

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## Introduction

Agricultural crops are attacked by a wide range of organisms, including insects, mites, nematodes, plant pathogens, weeds, rodents, birds and other pests. When their populations increase beyond acceptable levels, they cause substantial losses in crop yield and quality. Insect pests alone can damage crops by feeding on leaves, stems, roots, flowers, fruits and seeds or by transmitting plant diseases. For many decades, chemical pesticides have been an important tool for protecting crops. However, excessive dependence on pesticides can create several problems, including development of pesticide resistance, resurgence of target pests, outbreaks of secondary pests, destruction of pollinators and natural enemies, pesticide residues and environmental contamination. FAO describes Integrated Pest Management as an approach that carefully considers available pest-control techniques and integrates appropriate measures to discourage pest development while minimizing pesticide use and associated risks.

IPM therefore represents a shift from the traditional concept of “pest eradication” to pest management based on ecological and economic principles. It recognizes that not every pest observed in a field requires immediate control. Instead, farmers monitor pest populations and crop damage and intervene when economically justified.

## Concept of Integrated Pest Management

Integrated Pest Management is an ecosystem-based approach to crop protection in which different pest-management tactics are combined in a compatible manner. The objective is to maintain pest populations below levels that cause economically significant damage while minimizing adverse effects on people, beneficial organisms and the environment. The important point is that IPM does not mean simply combining many pesticides or using several control measures simultaneously. Rather, it is a decision-making process based on pest biology, crop condition, environmental factors, monitoring and economic considerations. Modern IPM emphasizes prevention, monitoring, diagnosis, biological control and other non-chemical methods, with pesticides used judiciously when necessary.

## Basic Principles of IPM

The major principles of integrated pest management are as follows:

### Prevention

Prevention is the first line of defense. Healthy crops are generally better able to tolerate pest attack. Proper land preparation, balanced fertilization, suitable irrigation, use of healthy planting material, sanitation, crop rotation and timely sowing can reduce pest establishment. Farmers should select varieties adapted to local agro-climatic conditions and, wherever available, use pest- and disease-resistant varieties.

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**Correct Identification of the Pest**

Effective management begins with correct identification. Different pests may produce similar symptoms, but their management requirements can be very different. Farmers should identify the pest, its developmental stage, nature of damage and associated natural enemies before selecting a control measure.

**Regular Monitoring and Surveillance**

Monitoring is the backbone of IPM. Fields should be inspected regularly for pest population, crop damage, natural enemies and environmental conditions. Various monitoring tools can be used, including: Direct visual observation, sweep nets, beat-sheet sampling, pheromone traps, light traps, yellow or blue sticky traps, soil sampling, plant sampling, weather-based forecasting, remote sensing and digital technologies. Regular monitoring helps detect pest outbreaks at an early stage and prevents unnecessary pesticide applications.



**Pheromone trap**




**Yellow sticky trap**

**Economic Threshold and Economic Injury Level**

The Economic Injury Level (EIL) is the lowest pest population density that causes economic damage equal to the cost of control. The Economic Threshold Level (ETL) is the pest population or damage level at which management action should be initiated to prevent the pest population from reaching the EIL. Therefore, farmers should avoid routine calendar-based spraying and instead make decisions based on monitoring and appropriate thresholds. FAO identifies economic levels, sampling, natural control and knowledge of pest biology and ecology as fundamental elements of IPM.

**Major Components of Integrated Pest Management**

IPM involves several complementary methods. Their relative importance depends on the crop, pest and agro-ecosystem.

**Cultural Control**

Cultural practices modify the crop environment in ways that reduce pest survival, reproduction or dispersal. Important cultural practices include: Crop rotation, timely sowing and planting, proper plant spacing, field sanitation, removal of crop residues and infested plant parts, destruction of volunteer plants, balanced fertilizer application, proper irrigation and drainage, intercropping, trap cropping, proper weed management.

**Mechanical Control**

Mechanical methods involve the physical removal or destruction of pests or infested plant material. Examples include: Hand-picking of egg masses and larvae, removal of infested shoots and fruits,

destruction of pest-infested residues, installation of barriers, use of nets, collection and destruction of egg masses, mechanical removal of weeds.

**Physical Control**

Physical methods make the environment unsuitable for pest survival or reproduction. Examples include: Solarization, heat treatment, cold treatment, light trapping, sticky traps, mulching, protective netting, temperature and humidity management in storage.

**Host Plant Resistance**

The use of resistant or tolerant varieties is one of the most economical and environmentally compatible components of IPM. Resistance may operate through: Antixenosis, Antibiosis, Tolerance. Resistant varieties can reduce pest establishment and multiplication and may reduce the need for pesticide applications. FAO recommends resistant cultivars and varieties as an important component of integrated crop protection.

**Biological Control**

Biological control is an important pillar of IPM. It involves the use or conservation of organisms that naturally suppress pests. The major groups of natural enemies include:

**Predators:** ladybird beetles, lacewings, predatory bugs, spiders and predatory mites.

**Parasitoids:** parasitoid wasps and flies that develop on or inside their hosts.

**Pathogens:** bacteria, fungi, viruses and nematodes that infect and kill pests.

Examples of microbial biopesticides include *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae* and *Nuclear Polyhedrosis Virus* preparations where appropriate.



**Lady bird beetle**

**Botanical and Bio-rational Approaches**

Botanical pesticides and bio-rational products can provide additional options within IPM. Neem-based products containing azadirachtin are widely recognized as useful components of insect pest management. Other bio-rational approaches include insect growth regulators, pheromones, attractants, repellents and microbial pesticides, depending on the pest and crop. Pheromone traps can be used for monitoring and, in selected pest systems, for mass trapping or mating disruption. These approaches can provide pest-specific management while reducing effects on non-target organisms.

**Biotechnological Approaches**

It is modern IPM technological tools such as: Pheromone-based mating disruption, sterile insect techniques, molecular diagnostics, pest forecasting models, Geographic Information System (GIS), remote sensing, automated pest identification, artificial intelligence-based image recognition, smartphone-based pest surveillance, precision pesticide application.

Digital technologies can support early detection and more precise decision-making. However, these technologies should complement, rather than replace, field observation and ecological knowledge.

**8. Chemical Control as a Component of IPM**

IPM does not completely eliminate the use of pesticides. Instead, chemical control is used only when necessary and when economically justified. When pesticide application becomes necessary, the following principles should be followed: Confirm the pest before treatment, apply pesticides only when monitoring indicates the need, select an effective and appropriately registered product for the crop and pest, follow the recommended dose and application method., use selective pesticides whenever possible, avoid unnecessary mixtures, rotate insecticides with different modes of action to delay resistance, follow the prescribed pre-harvest interval, Protect pollinators and natural enemies, use appropriate personal protective equipment, maintain records of pesticide applications and dispose of pesticide containers safely.

**Role of Farmers in IPM**

Farmers are the central decision-makers in successful IPM programmes. They should be trained to recognize major pests, beneficial insects and symptoms of pest damage as i.e., Pest identification, regular field scouting, maintenance of field records, recognition of beneficial organisms, use of pest-monitoring traps, knowledge of ETLs, safe pesticide handling. Farmer Field Schools and participatory approaches can be particularly useful because IPM is knowledge-intensive and requires farmers to understand their own agro-ecosystems.

**Advantages of Integrated Pest Management**

The major advantages of IPM include: Reduction in unnecessary pesticide use, lower risk of pesticide resistance, conservation of natural enemies, protection of pollinators, reduction of pesticide residues, improved environmental safety, potential reduction in pest-control costs, improved sustainability of crop production, improved long-term pest management.



**Crop heavily damaged by pests**

**Challenges in Adoption of IPM**

Despite its advantages, adoption of IPM can face several challenges. These include inadequate knowledge of pest identification, limited availability of biological control agents, insufficient monitoring facilities, difficulty in determining appropriate thresholds, lack of trained personnel,

farmers' dependence on quick pesticide-based solutions and inconsistent availability of quality biopesticides. IPM is generally more knowledge-intensive than calendar-based pesticide spraying. Farmers therefore require continuous technical guidance, demonstrations and field-level training. Extension agencies, agricultural universities, ICAR institutes, state agricultural departments, private organizations and farmer groups have important roles in strengthening IPM adoption.

**Future Prospects**

The future of IPM lies in combining traditional ecological knowledge with modern agricultural technology. Precision agriculture, artificial intelligence, digital pest surveillance, GIS, remote sensing, automated traps, improved biological control agents and climate-based pest forecasting can make IPM more accurate and timely. Climate change is also likely to influence pest distribution, seasonal occurrence and population dynamics. Consequently, pest surveillance and forecasting will become increasingly important. The future objective should be to develop location-specific, farmer-friendly, economically viable and environmentally safe IPM packages rather than relying on pesticide-intensive crop protection.

**Conclusion**

Integrated Pest Management is a practical and scientifically based approach for sustainable crop protection. It does not aim to eliminate every pest from an agricultural ecosystem. Instead, it seeks to understand the pest, crop, natural enemies and environmental conditions and then select the most appropriate combination of management practices. The foundation of IPM is prevention, monitoring, correct diagnosis and decision-making based on economic thresholds. Cultural, mechanical, physical, host-plant resistance, biological, botanical and biotechnological methods should receive priority, while chemical pesticides should be used judiciously when necessary. Successful IPM can contribute to safer food, reduced pesticide residues, conservation of biodiversity, protection of pollinators and natural enemies, and sustainable agricultural production.

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# FROM TROPICAL FRUIT TO FERMENTED BEVERAGE: THE POTENTIAL OF JACKFRUIT WINE

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## Introduction

Jackfruit (*Artocarpus heterophyllus* Lam.), a member of the family Moraceae, is one of the largest edible fruits cultivated in tropical and subtropical regions. It is valued for its distinctive aroma, sweet edible flakes, nutritional composition and versatility in food preparation. In India, jackfruit is consumed fresh and processed into a variety of products, including chips, jams, preserves, beverages, flour and confectionery.

## Could fermentation provide another avenue for utilizing this tropical resource?

Jackfruit wine offers one possible answer. Rather than viewing fermentation simply as a method of preserving fruit, it can be understood as a biological transformation in which microorganisms convert sugars and modify aroma precursors, acids and other constituents. The challenge is to translate this biochemical potential into a safe, consistent and sensorially acceptable product.

## The Hidden Chemistry of Jackfruit

The suitability of a fruit for fermentation depends on its chemical composition. Ripe jackfruit pulp contains soluble sugars, organic acids, minerals and various flavour-related compounds. Their concentrations vary with genotype, maturity, cultivation conditions and post-harvest handling. These differences are particularly important when jackfruit is considered as a raw material for wine production. A genotype with high soluble solids may provide more fermentable sugar, but sugar content alone does not determine the quality of the final beverage. Acidity, nutrient availability, pulp consistency, aroma precursors and microbial compatibility also influence the fermentation process.

A systematic comparison of genotypes could examine soluble solids, titratable acidity, pH, pulp yield, colour and selected biochemical attributes. These measurements would provide an initial understanding of raw-material suitability. Actual fermentation trials would still be required to establish which genotypes perform best, because fresh-fruit characteristics cannot reliably predict every aspect of fermentation or finished-product quality. Thus, jackfruit diversity may be relevant not only to fresh-fruit consumption but also to the development of specialized processing products.

## Fermentation: When Microorganisms Become Biochemical Engineers

Yeast, particularly Saccharomyces cerevisiae, converts fermentable sugars into ethanol and carbon dioxide through glycolysis and subsequent metabolic reactions. It also produces secondary metabolites, including esters, higher alcohols and organic acids, that influence the beverage's aroma and flavour. During fermentation, jackfruit's original volatile compounds may be lost, transformed or modified, while new compounds develop. Consequently, the final sensory profile depends on the fruit's composition, yeast strain and fermentation conditions (Tan *et al*., 2024).

## From Edible Bulb To Fermented Beverage

The production of jackfruit wine involves several interconnected operations. Each stage requires appropriate control to maintain product consistency and safety.

- **Raw-material selection:** Sound, appropriately mature fruit is selected. The edible bulbs are separated from the rind, core and seeds, depending on the intended product. Spoiled or mouldy fruit must be excluded.
- **Pulp preparation:** The edible portion is processed to obtain a suitable fermentable material. The preparation method influences juice recovery, suspended solids, pulp viscosity and the distribution of flavour compounds.
- **Must characterization:** The prepared material is assessed for soluble solids, pH and titratable acidity. These measurements help determine whether the substrate is suitable for the selected fermentation process.

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- **Controlled fermentation:** A suitable, food-grade yeast culture is introduced under validated conditions. Sugar availability, temperature, acidity, microbial activity and fermentation progress must be monitored.
- **Clarification and stabilization:** After fermentation, separation from sediment, clarification and suitable stabilization may be required. The precise approach depends on the beverage's composition and intended shelf life.
- **Quality verification and packaging:** The finished beverage is evaluated for ethanol concentration, residual sugars, acidity, sensory properties and microbiological stability. Hygienic packaging and suitable storage conditions are essential.

These stages are not interchangeable recipes. Their parameters must be established through controlled trials and results obtained for one genotype or formulation should not automatically be applied to all jackfruit materials. A study by Panda and colleagues (2016) demonstrated the feasibility of producing jackfruit-pulp wine using *S. cerevisiae* and evaluated its chemical composition and sensory acceptability.




***Figure 1. Major stages involved in production of Jackfruit wine***

**The Flavour Laboratory: Understanding What Makes A Fruit Wine Distinctive**

A fermented beverage may contain measurable ethanol and still have an unbalanced aroma or flavour. Product quality depends on the combined effects of sweetness, acidity, volatile compounds, colour, clarity and mouthfeel.

**Aroma: an invisible fingerprint**

Volatile compounds shape the aroma and flavour of fruit wines. Esters contribute fruity or floral notes, while higher alcohols and organic acids influence aroma complexity. Gas chromatography–mass spectrometry (GC–MS), particularly with headspace solid-phase microextraction (HS-SPME), can identify volatile compounds in jackfruit wine. However, their sensory impact depends on concentration, detection thresholds and interactions with other compounds.

**Taste and chemical balance**

The relationship between residual sugar and acidity affects perceived sweetness and tartness. Ethanol contributes to mouthfeel and warmth, while other fermentation products can influence the overall sensory experience. Measurements of pH, titratable acidity, residual sugars and ethanol provide complementary information. No single parameter is sufficient to establish product quality.

**Colour and biochemical composition**

Jackfruit pulp colour and biochemical composition may vary among genotypes. Some constituents can change during processing and fermentation through oxidation, enzymatic activity, chemical reactions or microbial metabolism. If the objective is to understand these changes, the raw pulp and finished beverage should be analysed separately. Claims about the retention of phenolics, carotenoids or other bioactive compounds should be supported by measurements rather than inferred from the composition of fresh fruit. This distinction is important because fermentation can substantially alter the original food matrix.

**Beyond Conventional Fermentation: Where Innovation May Emerge**

The future of jackfruit wine need not depend solely on reproducing an existing fermentation process. Several research directions could improve understanding of the raw material, microbial transformation and finished product.

- **Genotype-guided processing:** Jackfruit genotypes could be screened for soluble solids, acidity, pulp yield and selected aroma-related characteristics. Promising genotypes could then be evaluated in controlled fermentation trials.
- **Microbial selection:** Different yeast strains may produce different aroma profiles and fermentation outcomes. Comparative trials could evaluate fermentation efficiency, volatile composition, sensory quality and stability.
- **Data-driven fermentation:** Recording fermentation progress alongside sugar concentration, acidity, temperature and other quality indicators could help researchers identify relationships among process variables.
- **Analytical fingerprinting:** Combining physicochemical measurements, volatile profiling and sensory evaluation could provide a more complete description of jackfruit wine than conventional quality measurements alone.

These approaches are research opportunities, not established guarantees of improved beverage quality. Their value will depend on reproducible experiments and clear comparisons with appropriate controls.

**From Waste Management To Circular Bioeconomy**

Jackfruit processing generates materials such as rind, core and other fractions that may be discarded or underutilized. Their composition differs from that of the edible bulbsand each material requires an independent assessment of suitability for further processing. The concept of a circular bioeconomy encourages the efficient use of agricultural resources and the recovery of value from materials that might otherwise become waste. In jackfruit processing, potential routes include flour, pectin-rich materials, animal-feed applications where appropriate, extraction of selected compounds and fermentation-based products.

A 2026 study by Bensi and Divakar investigated wine production using formulations containing jackfruit bulbs and selected processing by-products. This demonstrates that alternative jackfruit fractions are being explored as fermentation substrates. Nevertheless, using a by-product does not automatically make a process sustainable or safe. Its microbial quality, composition, processing requirements, energy consumption, waste streams and final-product safety must all be evaluated. Some residues may be unsuitable for beverage production without substantial treatment.

**Safety, Responsible Consumption and Scientific Integrity**

Jackfruit wine is an alcoholic beverage, not a health supplement. The presence of phenolic compounds or antioxidant activity measured in a laboratory does not establish that consuming the beverage provides a health benefit. Alcohol concentration must be measured using an appropriate validated method. Product safety also depends on hygienic processing, controlled fermentation, microbial stability, suitable packaging and compliance with relevant food and alcohol regulations.

Research involving sensory evaluation of alcoholic beverages should follow applicable ethical requirements, including restrictions relating to age and informed consent. Scientific communication should distinguish between demonstrated findings and future possibilities. In particular, claims about nutritional superiority, health benefits, environmental sustainability or commercial profitability require evidence appropriate to each claim.

**The Road Ahead: Linking Fruit Diversity with Fermentation Science**

Jackfruit wine offers an opportunity to connect two areas that are often considered separately: the biological diversity of the fruit and the metabolic diversity of fermenting microorganisms. Fruit scientists can help characterize raw materials, identify promising genotypes and understand how maturity and composition affect processing. Microbiologists and food technologists can investigate fermentation performance, flavour development and product stability. Economists and sustainability researchers can evaluate processing costs, resource recovery and market feasibility.

The most informative future studies will combine these perspectives rather than focus exclusively on ethanol production. They could examine whether specific raw-material characteristics predict fermentation behaviour, whether selected yeast strains generate reproducible aroma profilesand whether alternative fruit fractions can be utilized safely and economically. Such research would help establish where jackfruit wine has genuine technical and commercial potentialand where further development is still required.

**Conclusion**

Jackfruit is more than a seasonal tropical fruit. Its diverse composition and substantial edible portion make it a candidate for a range of value-added applications, including controlled fermentation. Converting jackfruit pulp into wine shows how microbial metabolism can transform a horticultural

raw material into a product with a different chemical and sensory profile. Yet, the true opportunity lies not simply in producing an alcoholic beverage, but in understanding the science that governs raw-material selection, fermentation, aroma formation, quality and safety.

By linking jackfruit germplasm diversity with fermentation biotechnology and responsible resource utilization, researchers may identify more effective ways to use this valuable tropical crop. With careful validation, appropriate quality controlsand realistic economic assessment, jackfruit wine could become one option in a broader portfolio of jackfruit-based products. The future of jackfruit value addition will ultimately depend on a balance of scientific evidence, processing innovation, sustainability and practical feasibility.

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# LOW EXTERNAL INPUT SUSTAINABLE AGRICULTURE (LEISA): BUILDING RESILIENT FARMS WITH LOCAL RESOURCES

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**Abstract**
Low External Input Sustainable Agriculture (LEISA) is a farm-management approach that seeks to improve productivity and resilience by making better use of locally available resources while reducing unnecessary dependence on costly external inputs. Rather than eliminating external inputs completely, LEISA prioritizes recycling of crop residues and animal manure, legumes, crop rotation, agroforestry, soil organic matter management, water conservation and integrated pest management, with purchased inputs used strategically when local resources are insufficient. This article summarizes the principles, field practices, benefits and practical limitations of LEISA. It also presents a stepwise pathway for adoption at farm level. When supported by farmer knowledge, extension services, local institutions and appropriate markets, LEISA can strengthen soil health, resource-use efficiency, biodiversity and livelihood stability while improving the capacity of farms to cope climate and input-price risks.

**Keywords:** LEISA, resource recycling, soil health, farm diversification, climate resilience

## Introduction

Agriculture is expected to remain productive while facing soil degradation, water scarcity, climate variability and rising input costs. Sustainable farming therefore requires approaches that protect natural resources without ignoring farmers' need for dependable yields and income. LEISA emerged from this concern and was developed as an alternative to highly input-dependent production systems. Its central idea is to use ecological processes, farmer knowledge and locally available resources more effectively before relying on purchased inputs (Reijntjes *et al.*, 1992; Pretty, 2008).

## What LEISA means in practice

LEISA does not mean "zero external input" farming. It aims to minimize avoidable external inputs and improve the efficiency of those that are required. A LEISA farm first seeks nutrients, energy and biological regulation within the farm itself through residues, compost, manure, legumes, crop diversity, livestock integration and conservation practices. External fertilizer, seed, plant-protection products or irrigation may still be used when they correct genuine limitations and are applied safely and efficiently. This balance is consistent with integrated soil-fertility management, which combines organic resources, mineral nutrients and locally adapted agronomy rather than treating them as mutually exclusive choices (Vanlauwe *et al.*, 2010).

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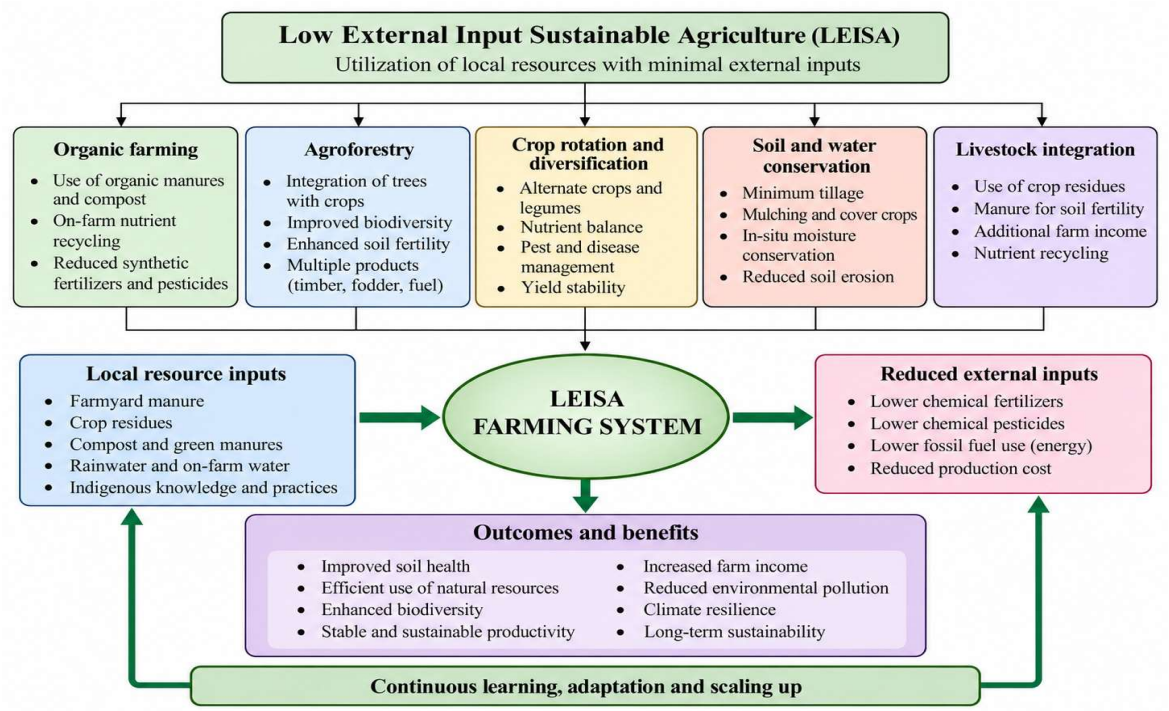



***Figure 1. Integrated LEISA system model linking local resources, crop, livestock, agroforestry, soil and water management with farm-level outcomes.***

**Core principles and field practices**

The first principle is resource recycling. Crop residues can be retained as mulch or converted to compost, while livestock manure can return nutrients and organic matter to the soil. Legumes contribute biologically fixed nitrogen and can be included as intercrops, green manures or rotation crops. These practices help reduce nutrient losses and improve soil biological activity.

The second principle is diversity and complementarity. Crop rotation, mixed cropping, agroforestry and crop-livestock integration spread production risks and allow different farm components to support one another. Trees may provide fodder, fuel, shade and nutrient recycling; livestock can use crop by-products; and manure can be returned to cropland. Farm diversity can also reduce dependence on a single crop or market.

The third principle is efficient management of soil, water and pests. Minimum or conservation tillage, surface cover, rainwater harvesting, careful irrigation and integrated pest management can reduce erosion, evaporation and unnecessary chemical use. LEISA also depends heavily on observation and farmer knowledge because practices must be adjusted to soil type, climate, labour availability and enterprise mix. Evidence from LEISA-oriented smallholder systems shows that ecological performance can improve when nutrient recycling and resource management are integrated with local conditions (Asminaya *et al.*, 2018).

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**A practical pathway for adoption**

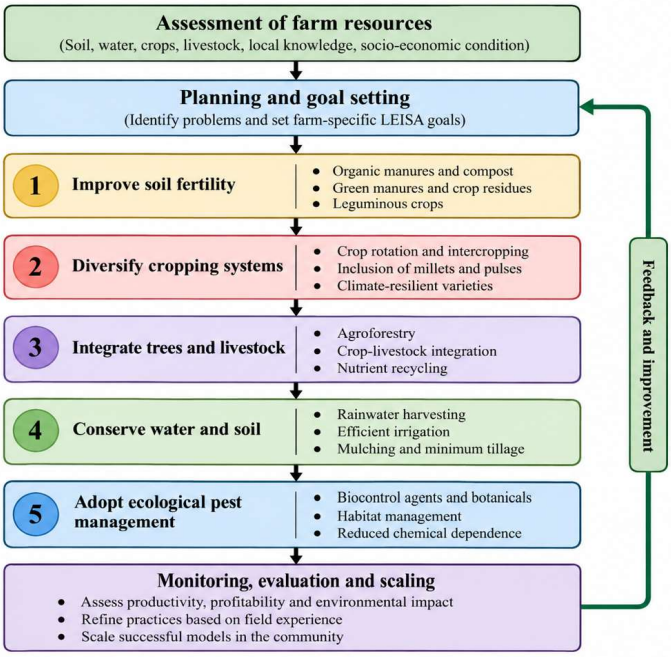



***Figure 2. Stepwise pathway for LEISA adoption from farm-resource assessment and planning to monitoring, evaluation and scaling.***

Farmers do not need to redesign the whole farm at once. A gradual transition is usually more realistic. The first step is to map current resources and identify the most expensive or wasteful external inputs. The next step is to improve recycling of biomass and nutrients, followed by greater crop diversity and, where feasible, livestock integration. Water, soil-cover and pest-management practices can then be strengthened. Purchased inputs are retained where they provide a clear response, but rates and timing are refined to avoid waste.

**Benefits and limitations**

A well-managed LEISA system can improve soil organic matter, nutrient cycling, water-use efficiency, biodiversity and resilience to external shocks. Lower dependence on purchased inputs can also reduce exposure to fertilizer, pesticide and fuel price volatility. Field experience in India has shown that low-external-input approaches can be integrated into smallholder rice systems when farmer learning and locally adapted management are emphasized (Balamatti *et al.*, 2017).

However, LEISA is knowledge-intensive. Compost preparation, diversified rotations, livestock integration and biological pest management may demand additional labour and management skill. Local biomass may also be insufficient to replace all nutrients removed in harvested produce. Hence, refusing all external inputs can reduce productivity and deplete soil fertility. The practical objective should be efficient and safe input use rather than input removal. Adoption can also be constrained by small landholdings, labour shortages, limited access to credit, weak extension services and uncertain markets for diversified products. Community composting, custom-hiring services, farmer-producer organizations, local seed systems and extension support can help reduce these barriers.

**Future opportunities**

LEISA can be strengthened by combining traditional ecological knowledge with modern tools such as soil testing, weather advisories, low-cost moisture sensors and decision-support systems. These

tools can help farmers identify where external inputs are truly needed and where biological or locally available resources can substitute for them. Climate-resilient varieties, water harvesting and diversified farming systems will become increasingly important as weather variability intensifies.

The broader value of LEISA lies in its systems approach: productivity, soil health, water, biodiversity, household income and risk are considered together rather than as isolated targets. Such approaches are increasingly important under climate change, which affects crop growth, pest pressure, water availability and farm profitability simultaneously (Malhi *et al.*, 2021).

**Conclusion**

LEISA offers a practical pathway toward more resilient and resource-efficient agriculture by prioritizing local resources, ecological processes and farmer knowledge while using external inputs selectively. Its strength lies in recycling nutrients, maintaining living soils, diversifying farm enterprises and reducing avoidable waste. Successful adoption requires site-specific management, reliable extension support and realistic recognition that some external inputs may still be necessary. When implemented gradually and evaluated on productivity, cost, soil health and resilience, LEISA can help farmers reduce dependency without compromising the long-term productive capacity of the farm.

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# MANATEES - THE GENTLE GIANTS OF THE SEA

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## Introduction

Picture a large, rounded animal gliding quietly through a shallow river, its paddle-shaped tail sweeping gently as it grazes on aquatic plants. This is the manatee, often called the "sea cow". It is known for its calm behaviour and plant-based diet. Manatees look slow and harmless, but they are well adapted to aquatic life and move efficiently through rivers, estuaries, coastal waters and freshwater springs.

Manatees belong to the order Sirenia, a group of fully aquatic, plant-eating mammals that also includes the dugong. Three living species are recognised: the West Indian manatee (*Trichechus manatus*), the Amazonian manatee (*T. inunguis*) and the West African manatee (*T. senegalensis*). The West Indian manatee has two subspecies, the Florida manatee and the Antillean manatee (U.S. Fish & Wildlife Service, 2026; NOAA, 2026).



***"An adult West Indian manatee (Trichechus manatus)***
***Photo: Manatee, Ramos, Keith/USFWS, Public Domain, https://www.fws.gov/media/manatee-1."***

**Scientific Classification**

| **Rank** | **Name** |
|---|---|
| Kingdom | Animalia |
| Phylum | Chordata |
| Class | Mammalia |
| Order | Sirenia |
| Family | Trichechidae |
| Genus | *Trichechus* |
| Species (example) | *Trichechus manatus* (West Indian manatee) |

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**A Mammal Built for Aquatic Life**

Manatees have a large, streamlined body, two flippers and a broad, paddle-shaped tail. The flippers help them steer, move through vegetation and handle food, while the tail provides the main thrust for swimming. Adult West Indian manatees are commonly 9-10 feet long, and some exceed 13 feet. Adults often weigh over a thousand pounds, and the largest individuals can reach about 3,500 pounds (U.S. Fish & Wildlife Service, 2026).

Despite their fish-like shape, manatees are mammals. They breathe air through lungs, give birth to live young and nurse their calves on milk. One of their most surprising relationships is with elephants. Both belong to the evolutionary group Paenungulata and share a distant common ancestor.

**Where Do Manatees Live?**

The West Indian manatee lives in warm coastal and inland waters of the south-eastern United States, the Caribbean, Central America and parts of northern and eastern South America. Florida manatees use coastal waters, rivers, springs and other warm-water habitats, and they may travel long distances as water temperature changes.

Manatees are sensitive to cold. In Florida, they move to warm-water refuges when temperatures fall, so changes to natural warm-water sites can affect their survival and seasonal movements (U.S. Fish & Wildlife Service, 2026; Runge *et al*., 2017).




Range of the West Indian manatee

**A Vegetarian Giant**

Manatees are herbivores. They feed on seagrasses, freshwater aquatic plants and, in some areas, vegetation growing along shorelines. They spend much of the day feeding and can eat large quantities of plant material.

These grazing shapes aquatic habitats and moves nutrients through the ecosystem, linking plant production to the wider food web. NOAA describes manatees as important parts of healthy aquatic ecosystems, closely tied to seagrass and other aquatic vegetation (NOAA, 2026).

**Life, Behaviour and Reproduction**

Manatees are generally slow-moving, peaceful animals. They rest, feed, travel and interact in shallow, sheltered waters. Their calm manner should not be mistaken for weakness, because they can swim in short, faster bursts when needed.

The bond between a mother and her calf is especially strong. The calf stays close to its mother and learns how to feed and move through the habitat. Manatees reproduce slowly, so the survival of adults and calves is critical for population recovery.

**The Manatee - Dugong Connection**

Manatees and dugongs are the only living members of the order Sirenia. Both are plant-eating aquatic mammals, but they differ in tail shape. Manatees have a broad, rounded, paddle-like tail, whereas dugongs have a whale-like fluked tail. Together they show how related mammals can adapt to different aquatic environments.

**When a Gentle Giant Meets a Fast Boat**

One of the most serious threats to manatees is collision with motorised boats. Manatees often use shallow waters where boats also travel. Research on Florida manatees shows that a large proportion of recorded dives were shallow enough to place the animals within striking depth of a boat (Hostetler *et al*., 2016).

Boat strikes can cause severe injury or death. The propeller scars on the backs of many manatees are clear evidence of repeated encounters with vessels. Recent research continues to identify watercraft strikes as a major conservation concern and explores how manatees' perception of boat noise could help improve management (Bauer *et al*., 2026).

**Other Threats to Survival**

Boats are not the only danger. Habitat loss, declining aquatic vegetation, pollution, harmful algal blooms, cold stress, entanglement in fishing gear and changes to warm-water refuges also affect manatees. In Florida's Indian River Lagoon, manatee die-offs have occurred in an environment affected by algal blooms and seagrass decline (Miller *et al*., 2022).

These threats are linked. Poor water quality encourages algal blooms, which reduce water clarity and damage aquatic plants. Less vegetation means less food for plant-eating animals such as manatees.

**Why Manatees Matter**

Manatees are large herbivores that connect aquatic plants with the wider food web. Their health can also reflect the health of their habitat. A decline in manatee condition may point to deeper problems such as poor water quality, loss of aquatic vegetation or habitat disturbance.

**Conservation Status and Legal Protection**

| | |
|---|---|
| **Scientific name** | *Trichechus manatus* |
| **Common names** | West Indian manatee, Caribbean manatee, sea cow |
| **IUCN Red List (global)** | Vulnerable (VU) |
| **CITES** | Appendix I |
| **U.S. Endangered Species Act** | Threatened (Florida manatee, since 2017) |
| **Main pressures** | Boat collisions, habitat degradation, loss of aquatic vegetation, pollution |
| **Priority action** | Protect habitat and reduce preventable human-caused deaths |

**Conservation: Protecting the Habitat, Not Just the Animal**

Effective manatee conservation means more than rescuing injured animals. It means protecting the habitats that populations depend on. Key measures include protecting warm-water refuges, maintaining healthy seagrass and freshwater plant communities, improving water quality, slowing boat speeds in manatee areas, preventing harmful disturbance, and responding quickly to injured or stranded animals.

The Florida manatee was reclassified from Endangered to Threatened under the U.S. Endangered Species Act in 2017, after long-term conservation efforts and population recovery. The U.S. Geological Survey stresses that continued research and management are still needed, because the species faces multiple threats (USGS, 2025).

**Conclusion**

Manatees are far more than gentle “sea cows”. They are specialised aquatic mammals that connect plant growth, nutrient cycling and animal life in freshwater and coastal ecosystems. Their slow, peaceful nature makes them endearing, but it also makes them vulnerable to human activity.

The future of manatees depends on healthy aquatic habitats and fewer preventable human-caused deaths. When boats slow down, habitats are protected and water quality improves, manatees get a better chance to survive. Protecting these gentle giants ultimately means protecting the waters they call home.

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# FROM JAYANTI ROHU TO MAHA MAGUR: BREEDING BETTER FISH FOR INDIA'S AQUACULTURE FUTURE

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## Introduction

Aquaculture has become one of the fastest-growing food-producing sectors worldwide. Increasing demand for aquatic foods, pressure on capture fisheries, population growth, and the need to improve resource-use efficiency have increased the importance of sustainable aquaculture production. Genetic improvement through selective breeding is one of the major approaches available for increasing the biological and economic efficiency of cultured fish (Gjedrem, 2016; Gjedrem *et al*., 2012). Selective breeding involves identifying individuals with desirable inherited characteristics, using them as parents, evaluating their offspring, and repeating the process over successive generations. Properly designed programmes can increase growth rate, improve survival and feed efficiency, enhance disease resistance or tolerance, and improve adaptation to particular production environments (Gjedrem & Baranski, 2009; Gjedrem *et al*., 2012). Unlike simple selection of the largest fish in a pond, a scientific breeding programme estimates genetic merit while accounting for environmental effects and relationships among individuals. The long-term objective is to increase the frequency of favourable alleles while maintaining sufficient genetic diversity to sustain improvement over generations (Gjedrem & Baranski, 2009; Lind *et al*., 2012).

## What Is Selective Breeding?

Selective breeding is a systematic genetic-improvement process in which fish possessing desirable heritable characteristics are identified and selected as broodstock. Their offspring are subsequently evaluated, and individuals with superior genetic merit are selected for the next generation.

## The basic principle can be summarized as:

Identify superior fish → select parents → controlled mating → evaluate offspring → select superior offspring → repeat across generations.

The response to selection depends on the amount of additive genetic variation present in the population, the accuracy of selection, selection intensity, generation interval, and appropriate breeding-program design (Gjedrem, 1983; Gjedrem, 2016). Scientific breeding programmes therefore use individual identification, pedigree recording, performance testing, family evaluation, estimation of breeding values, and controlled mating. These approaches help separate genetic differences from environmental effects and reduce the risk of selecting fish simply because they happened to experience better growing conditions (Gjedrem & Baranski, 2009).

## Why Do We Need Selectively Bred Fish?

Aquaculture populations derived from poorly managed or repeatedly reused broodstock can experience loss of genetic diversity and increased relatedness. Such problems may reduce long-

term breeding response and, in severe cases, contribute to inbreeding depression. Maintaining adequate effective population size and managing relationships among brood fish are therefore essential components of sustainable breeding programmes (Lind *et al*., 2012).

**Selective breeding can target economically important characteristics such as:**

- Faster growth;
- Improved feed efficiency;
- Increased survival;
- Disease resistance or tolerance;
- Adaptation to local environmental conditions;
- Improved carcass or fillet characteristics; and
- Reproductive performance.

Genetic improvement can permanently accumulate across generations when superior breeding animals are retained as parents. This differs from improvements resulting solely from better feed or management because genetic gain can be transmitted to subsequent generations (Gjedrem & Baranski, 2009; Gjedrem *et al*., 2012). The economic benefit of faster growth can arise from shortening the production cycle and increasing output from available infrastructure. Nevertheless, genetic improvement should be evaluated together with nutrition, health management, water quality, and biosecurity and farm management because genetic gain alone cannot compensate for poor production conditions.

**How Are Superior Fish Selected?**

Modern selective breeding is considerably more sophisticated than simply choosing the largest fish. A structured programme may include the following stages.

**Step 1: Establish a genetically diverse base population**

A breeding population should contain adequate genetic variation for the traits of interest. Founder populations may be derived from multiple geographic or genetic sources, provided that biosecurity and genetic-management considerations are addressed. The GIFT tilapia programme, for example, established a synthetic base population involving African and Asian genetic resources (Eknath *et al*., 2007; Bentsen *et al*., 2017).

**Step 2: Identify desirable traits**

Breeding objectives should be based on biological and economic importance. Growth, survival, disease resistance, feed efficiency, carcass yield, reproductive performance and environmental tolerance may all be included depending on the species and production system (Gjedrem *et al*., 2012).

**Step 3: Measure individual performance**

Fish are individually identified, and phenotypic information is collected under controlled or standardized production conditions. Traits may be recorded at multiple stages of production.

**Step 4: Estimate genetic merit and select superior individuals**

Selection should ideally be based on estimated breeding values or other measures of genetic merit rather than phenotype alone. Family information and pedigree records can improve selection accuracy (Gjedrem & Baranski, 2009).

**Step 5: Controlled mating**

Controlled mating is used to produce known families and manage genetic relationships. Appropriate mating designs reduce the probability of excessive inbreeding while retaining genetic variation.

**Step 6: Evaluate offspring**
The next generation is evaluated under standardized conditions. Where possible, common-environment or communal-rearing designs are used so that environmental differences do not obscure genetic differences.

**Step 7: Continue selection**
Superior individuals are selected for the next generation. Repeated selection can result in cumulative genetic improvement when the breeding programme is appropriately designed and sufficient genetic variation remains (Gjedrem, 2016).

**Some Important Selectively Bred Fish**
Selective breeding has transformed aquaculture in several parts of the world. From tropical tilapia farming in Africa and Asia to salmon production in Europe and South America, genetic improvement programmes have helped develop fish populations with better growth, feed efficiency, survival and other economically important characteristics. Several countries have established long-term breeding programmes that combine conventional selection, performance testing, pedigree recording and modern genomic technologies. The following examples illustrate the global progress of selective breeding in aquaculture (Gjedrem *et al*., 2012; Boudry *et al*., 2021).

**1. Nile Tilapia (*Oreochromis niloticus*) – A Global Success Story**
**Major regions:** Africa, Asia and Latin America
Nile tilapia is one of the most successful examples of genetic improvement in aquaculture. The GIFT (Genetically Improved Farmed Tilapia) programme, initiated in the late 1980s, developed improved tilapia through systematic selection and the evaluation of genetic resources from different populations.

The programme demonstrated that successive generations of selection could substantially improve growth performance compared with the original base populations. Improved tilapia strains have subsequently contributed to aquaculture development in numerous countries (Eknath *et al*., 2007 & Bentsen *et al*., 2017).

**2. Atlantic Salmon (*Salmo salar*) – Norway, Chile and Scotland**
**Major regions:** Norway, Chile, Scotland and other salmon-producing countries
Atlantic salmon is a leading example of intensive, science-based selective breeding. Commercial breeding programmes began several decades ago, and the industry now uses sophisticated genetic evaluation methods, including genomic selection. Breeding objectives extend beyond growth to include resistance to important diseases and parasites, age at sexual maturation, product quality and performance under commercial farming conditions. The combination of genetic improvement, nutrition, health management and advanced production technology has helped make salmon farming a major global aquaculture industry (Boudry *et al*., 2021).

**3. Rainbow Trout (*Oncorhynchus mykiss*) – North America and Europe**
**Major regions:** United States, Canada and several European countries
Rainbow trout has a long history of domestication and selective breeding. Breeding programmes have improved growth, feed efficiency, carcass characteristics and adaptation to intensive production systems. More recent programmes have also investigated genetic resistance to specific diseases and improved performance under varying environmental conditions (Boudry *et al*., 2021).

**4. Common Carp (*Cyprinus carpio*) – China and Central and Eastern Europe**

**Major regions:** China, Hungary, Poland, the Czech Republic and other carp-producing countries

Common carp is one of the world's oldest domesticated aquaculture fish. Over many generations, farmers and researchers have developed different strains and varieties through domestication, selective breeding and, in some cases, hybridization. Modern breeding programmes aim to improve growth, body shape, feed utilization, survival and adaptation to particular production systems. In Central and Eastern Europe, carp breeding has traditionally been associated with pond farming, while China has developed diverse strains for different aquaculture environments (Vandeputte, 2003).

**5. Channel Catfish (*Ictalurus punctatus*) – United States**

**Major regions:** United States, particularly the southern states

Channel catfish is an important species in the US freshwater aquaculture industry. Genetic improvement programmes have focused on growth, survival, carcass yield and disease resistance. Selective breeding has also been used alongside hybridization with blue catfish (*Ictalurus furcatus*) in commercial production. It is important to distinguish these approaches: selection improves inherited characteristics within a breeding population, whereas hybridization crosses different species or strains (Kumar *et al*., 2020).

**6. Pangasius or Striped Catfish (*Pangasianodon hypophthalmus*) – Vietnam**

**Major regions:** Vietnam and other Southeast Asian countries

Pangasius has become a major aquaculture and seafood-export species, particularly in Vietnam's Mekong Delta. Its commercial success has encouraged the development of improved broodstock management and genetic selection programmes. Breeding objectives include faster growth, improved survival, feed utilization and reliable performance under high-density farming conditions.

**7. Grass Carp (*Ctenopharyngodon idella*) – China**

**Major regions:** China and other Asian countries

China has developed extensive breeding programmes for several freshwater aquaculture species, including grass carp. Selection has targeted commercially valuable characteristics, such as growth, body size, survival and adaptation to different culture systems. Grass carp is particularly important in freshwater aquaculture because of its herbivorous feeding habit, which allows farmers to use plant-based feeds and aquatic vegetation as part of production systems.

**8. Gilthead Seabream (*Sparus aurata*) – Mediterranean Countries**

**Major regions:** Greece, Turkey, Spain and other Mediterranean aquaculture countries

Gilthead seabream is a major marine aquaculture species. Selective breeding programmes have increasingly focused on growth, feed efficiency, survival and resistance to specific diseases. As marine aquaculture expands, improved broodstock and more reliable genetic performance are becoming important for reducing production costs and improving competitiveness (Thorland *et al*., 2026).

**9. European Seabass (*Dicentrarchus labrax*) – Mediterranean and European Countries**

**Major regions:** Greece, Turkey, Spain, Italy and other Mediterranean countries

European seabass is another commercially important marine fish benefiting from genetic improvement. Breeding programmes aim to improve growth, survival, feed efficiency and resistance to diseases that affect intensive farming. The species illustrates how selective breeding is

increasingly being applied beyond freshwater aquaculture to commercially valuable marine fish (Boudry *et al*., 2021).

**10. Japanese Yellowtail (*Seriola quinqueradiata*) – Japan**

**Major region:** Japan

Japanese yellowtail, locally known as *buri*, is an important marine aquaculture species. Its farming industry has explored breeding and genetic improvement to enhance growth, flesh quality, disease resistance and production efficiency. As marine aquaculture moves towards more controlled and sustainable production systems, systematic broodstock management and selective breeding are becoming increasingly important.

**11. Atlantic Cod (*Gadus morhua*) – Norway and Northern Europe**

**Major regions:** Norway and other northern European countries

Atlantic cod has been investigated for selective breeding in response to interest in developing commercial marine aquaculture. Research and breeding efforts have examined growth, maturation, survival and production characteristics. However, the commercial development of cod farming has experienced significant economic and biological challenges. This example demonstrates that genetic improvement alone cannot guarantee the commercial success of an aquaculture species (Gjerde *et al*., 2004).

**12. Barramundi or Asian Seabass (*Lates calcarifer*) – Australia and Southeast Asia**

**Major regions:** Australia, Thailand, Singapore and other Southeast Asian countries

Barramundi is an important tropical and subtropical aquaculture species. Breeding programmes have targeted growth, survival, disease resistance and adaptation to freshwater, brackishwater and marine production systems. The species is particularly promising for diversified aquaculture because it can be cultured in different environments, although performance varies with strain, management and local conditions (Macbeth and Palmer, 2011).

**Selectively Bred Fish and Indian Aquaculture**

India possesses considerable genetic diversity in freshwater fish and has developed selective-breeding programmes for several economically important species. The most extensively documented example is Jayanti Rohu, while newer programmes include genetically improved Catla, common carp for saline environments and Indian Magur.

**1. Rohu – *Labeo rohita*- Jayanti Rohu**

Rohu is one of the most important Indian major carps and a cornerstone of freshwater aquaculture in South Asia. Because of its excellent consumer acceptance, adaptability and market value. Jayanti Rohu is the first genetically improved fish variety developed in India, created through a selective breeding program initiated in 1992 by the ICAR-Central Institute of Freshwater Aquaculture (ICAR-CIFA) in collaboration with Institute of Aquaculture Research (AKVAFORSK) in the year 1992. Bred from diverse founder populations across five major North Indian Rivers and local stocks, this strain of Rohu (*Labeo rohita*) achieves an impressive 17% to 18% (Das Mahapatra *et al*., 2007). genetic gain per generation for growth traits. This allows the fish to reach market size roughly two months faster than traditional local stocks, resulting in nearly 50% higher economic returns for aquaculture farmers. Furthermore, newer generations—known as AhR-Jayanti Rohu—are specially bred for enhanced disease resistance against *Aeromonas hydrophila*, a common bacterial pathogen (Sahoo *et al*., 2004).. Distributed nationwide through authorized multiplier units, Jayanti Rohu adapts

exceptionally well to various farming environments, offering superior survival rates and higher efficiency for the aquaculture industry.

**2. Catla – *Catla catla* -Amrit Catla**

Catla is another major Indian carp with high commercial importance. Its rapid growth and preferred feeding zone make it particularly valuable in composite carp culture. Amrit Catla is a genetically improved strain of the Catla fish (*Labeo catla*) developed through selective breeding by the ICAR-Central Institute of Freshwater Aquaculture (ICAR-CIFA) in Bhubaneswar. Officially launched on September 12, 2024. This new variety is engineered to significantly boost aquaculture productivity and fish farmer incomes. It achieves roughly a 15% genetic gain per generation, allowing it to reach an impressive average weight of 1.8 kg in one year within polyculture systems, compared to just 1.2 kg for traditional local strains. To ensure widespread dissemination, the strain has been handed over to the National Freshwater Fish Brood Bank (NFFBB), providing farmers with a higher-yielding option that offers better market size and enhanced overall farm efficiency (Government of India, 2024).

**3. Common Carp – *Cyprinus carpio*- Saline Carp**

Common carp is among the world's most widely cultured freshwater fish. It has been subjected to breeding and genetic improvement programmes in many countries. The species is particularly suitable for breeding programmes because of its relatively well-established reproductive biology and wide environmental adaptability. Genetically improved strain of the common carp (*Cyprinus carpio*) developed through a selective breeding program at the ICAR-Central Institute of Fisheries Education (ICAR-CIFE) Rohtak Centre in Haryana for a candidate species for culture in degraded inland saline soils of India. This mega-breeding initiative was established to transform the vast, degraded inland saline lands of North India into productive aquaculture zones. By pooling diverse geographic stocks from multiple Indian states to build a robust base population, scientists utilized Best Linear Unbiased Prediction (BLUP) based selection to isolate traits for rapid growth and high salinity tolerance. The resulting "Saline Carp" delivers an impressive 28% higher growth rate than traditional common carp, comfortably tolerates inland groundwater salinity levels between 0 to 8 ppt, and can withstand the extreme temperature fluctuations of North India. Reaching a marketable size of 800–1000 grams in just 7 to 10 months.

**4. Indian Magur – *Clarias magur* – Maha Magur**

Indian Magur is a highly valued freshwater catfish with considerable potential for aquaculture. Its air-breathing ability enables it to tolerate relatively stressful culture environments. Maha Magur is a genetically improved, fast-growing strain of the indigenous Indian catfish (*Clarias magur*) developed through an intensive selective breeding program by the ICAR-Central Institute of Fisheries Education, Mumbai. Because the rapid-growing African catfish (*Clarias gariepinus*) is legally banned in India, scientists initiated this program to boost the harvest body weight of native Magur while conserving the indigenous catfish population. This ongoing genetic selection program targets superior progeny inheritance, yielding a hardier variety with accelerated growth rates and high survival capabilities compared to traditional, non-selected farm stocks.

**From Conventional Selection to Genomic Selection**

Fish breeding has entered a new technological era. Traditional selective breeding depends largely on measuring observable characteristics, or phenotypes. Modern breeding programmes can also use molecular markers and genomic information. **Genomic selection** uses information from

thousands of genetic markers distributed across the genome to estimate the breeding value of individual fish. This can be particularly useful for traits that are:

- Difficult or expensive to measure
- Expressed late in life
- Sex-dependent
- Associated with disease challenge
- Related to reproductive characteristics

For example, instead of waiting until fish reach harvest size to identify superior breeders, genomic information may help predict their genetic potential at an earlier stage (Boudry *et al*., 2021).

**Selective Breeding and Disease Resistance**

Disease is one of the major constraints facing modern aquaculture. Vaccination, biosecurity, improved water quality and better nutrition are important tools for disease management. However, genetic improvement offers another promising approach. If some fish naturally show greater resistance or tolerance to a particular disease, these individuals can potentially be incorporated into breeding programmes. Over successive generations, the frequency of favorable genetic characteristics may increase.

This could help reduce:

- Mortality
- Medication costs
- Production losses
- Dependence on therapeutic treatments

However, disease resistance breeding must be conducted carefully and should complement—not replace—good farm management and biosecurity.

**Maintaining Genetic Diversity: The Hidden Challenge**

Selective breeding is powerful, but it must be managed responsibly. One major risk is inbreeding. If closely related fish are repeatedly crossed, genetic diversity may decline. This can result in reduced growth, poor reproduction, increased susceptibility to diseases and other undesirable effects. Therefore, successful breeding programmes must maintain adequate effective population size and carefully monitor pedigrees and genetic relationships. The goal is not simply to produce the biggest fish. The goal is to produce genetically superior, healthy and productive fish while maintaining sufficient genetic diversity for long-term sustainability**.**

**Selective Breeding at the Farm Level**

The benefits of genetic improvement ultimately reach farmers only when improved broodstock and quality seed are made available. Farmers should therefore obtain seed from reliable hatcheries and scientifically managed breeding programmes. Simply selecting the largest fish from a pond and repeatedly using them as broodstock does not necessarily constitute a scientifically designed selective-breeding programme.

Farm-level broodstock management should include:

- Proper identification of brood fish
- Maintaining records
- Avoiding repeated mating among relatives
- Periodic introduction of unrelated genetic material where appropriate
- Selecting fish based on performance

- Maintaining adequate broodstock numbers
- Maintaining good nutrition and health

**The Future: Fish Designed for Changing Climates**

Climate change is creating new challenges for aquaculture. Increasing temperature, fluctuating rainfall, water scarcity, salinity intrusion, emerging diseases and changes in water quality can affect fish production. Selective breeding can contribute to climate-resilient aquaculture by developing fish that perform better under challenging environmental conditions. Future breeding programmes may therefore focus on heat tolerance, low-oxygen tolerance, salinity tolerance, disease resistance, efficient feed utilization and resilience to environmental fluctuations**.**

This will become increasingly important as aquaculture expands into new geographical and climatic environments.

**Beyond Growth: Breeding for Sustainable Aquaculture**

The future of selective breeding should not be measured only by kilograms of fish produced. A truly sustainable breeding programme should aim for fish that: Grow efficiently + survive better + use less feed + tolerate environmental stress + resist disease + maintain reproductive fitness + retain genetic diversity. Such fish could reduce the environmental footprint of aquaculture while increasing farmer profitability.

**Conclusion**

Selective breeding is a long-term investment in the genetic foundation of aquaculture. When supported by sound science, responsible broodstock management and effective seed distribution, it can help farmers produce more fish with fewer resources and contribute to sustainable food and nutritional security worldwide. The success of genetically improved tilapia, salmonids and several other species demonstrate what can be achieved through systematic genetic selection. For India, the opportunity is even greater. India is endowed with an extraordinary diversity of indigenous fish species, many of which hold enormous potential for aquaculture. Successful selective breeding efforts in species such as Rohu, Catla, Magur and Common Carp have demonstrated the potential of genetic improvement to enhance fish production. Expanding these programmes to other commercially important species, while maintaining genetic diversity and long-term breeding objectives, can pave the way for a more productive, profitable, climate-resilient and sustainable aquaculture industry in India.

The aquaculture of tomorrow will not depend only on better feeds, better ponds and better technologies**.** It will increasingly depend on better fish**.** And developing those better fish begins with a simple principle: Select the best, breed the best, evaluate scientifically—and improve generation after generation.

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# ION-SELECTIVE FIELD-EFFECT TRANSISTORS: CHIP-BASED SENSORS FOR DETECTING IONS

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**Abstract**
Ion-selective field-effect transistors (ISFETs) are tiny solid-state sensors that turn the concentration of ions in a liquid into an electrical signal. First developed in 1970, they replace the metal gate of a silicon transistor with an ion-sensitive surface and a reference electrode. With suitable coatings, they can measure pH and ions such as potassium, ammonium, and nitrate. This article explains how an ISFET works, why it is attractive compared with the glass electrode, and where it is used, from DNA sequencing to soil and water testing. It also discusses drift, reference electrode design, and interference, and stresses the need for regular calibration and validation against standard methods.

**Keywords**: ISFET, ion sensing, pH, soil sensors, biosensors

## Introduction

Many everyday decisions depend on knowing how acidic or alkaline a liquid is, or how much of a particular ion it contains. Farmers check soil pH before applying lime or fertiliser, doctors monitor blood chemistry, and food processors watch fermentation. The familiar glass pH electrode has served these needs for decades, yet it is fragile, relatively bulky, and difficult to miniaturise. Engineers therefore looked to the same silicon technology that powers mobile phones and asked whether a chip could sense chemistry directly. The ion-sensitive field-effect transistor (ISFET) is the result. First reported by Piet Bergveld in 1970, it is a tiny solid-state sensor that converts the concentration of ions in a liquid into an electrical signal (Bergveld, 1970). When it is covered with a selective membrane so that it responds to one ion rather than hydrogen ions, it is commonly called an ion-selective field-effect transistor.

## From transistor to chemical sensor

A conventional metal-oxide-semiconductor field-effect transistor (MOSFET) is an electronic switch. A voltage applied to its metal gate controls how easily current flows between two terminals called the source and the drain. The gate acts like a tap: a small change in gate voltage produces a large change in current.

In an ISFET the metal gate is removed and the insulating layer beneath it is exposed to the solution being tested. A reference electrode dipped in the same solution sets a fixed electrical potential, taking the place of the gate contact (Bergveld, 2003). Figure 1 shows this arrangement. Because the transistor is already built to be highly sensitive to charge near the gate, any change in charge at the insulator surface alters the current and can be measured.

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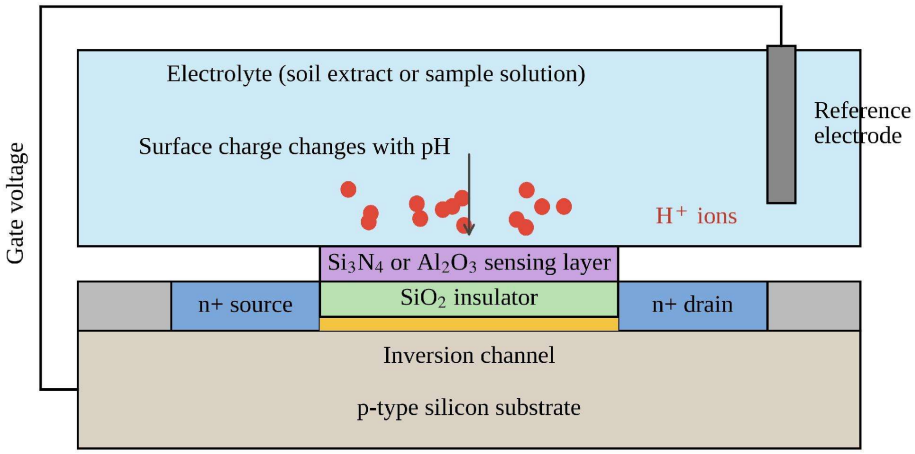



***Figure 1: Simplified cross-section of an ISFET showing the sensing layer, insulator, source, drain, and reference electrode***

**How does an ISFET sense ions?**

The insulating surface of an ISFET carries chemical groups that can gain or lose hydrogen ions. In an acidic solution the surface tends to pick up hydrogen ions and becomes more positively charged; in an alkaline solution it loses them and becomes more negative. This surface charge shifts the voltage at which the transistor starts to conduct, known as the threshold voltage. By measuring that shift, or by holding the current constant and recording the voltage needed to do so, the pH of the solution can be read electronically (Bousse *et al*., 1983).

The size of the response depends strongly on the surface material. Silicon dioxide on its own responds poorly. Layers of silicon nitride, aluminium oxide, or tantalum oxide respond much more reliably, and good devices approach the theoretical limit of about 59 millivolts per pH unit at room temperature (Bergveld, 2003; Bousse *et al*., 1983). Figure 2(a) illustrates this relationship for an ideal sensor and for a slightly weaker, more typical one.

**From pH to other ions**

To measure ions other than hydrogen, the sensing surface is coated with a thin membrane that allows mainly one ion to interact with it. Such membranes contain molecules called ionophores that bind a chosen ion, for example potassium, ammonium, or nitrate. The bound ions change the charge at the surface, and the transistor converts this into a voltage signal in the same way as for pH (Bergveld, 2003; Lee *et al*., 2009). In principle, one chip can carry several sensing regions, each coated differently, to measure a small panel of ions at once.

Enzymes can also be placed on the surface. The enzyme converts a target substance, such as urea or glucose, into products that change the local pH, and the ISFET detects that change. This idea has supported research on devices for medical diagnosis and food testing (Lee *et al*., 2009).

**Why are ISFETs attractive?**

ISFETs offer several practical advantages over glass electrodes. They are very small, so only a drop of liquid is needed. They respond quickly, are mechanically robust, and can be built using standard semiconductor manufacturing, which allows large numbers of identical sensors to be made at low cost per unit. Many designs can also be stored dry, which is convenient for field use. Their output is

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already an electrical signal, so they connect easily to microcontrollers, wireless modules, and data loggers (Bergveld, 2003).

**Where are ISFETs used?**

The best-known large-scale application is in DNA sequencing. Each time a nucleotide is added to a growing DNA strand, a hydrogen ion is released. A chip containing millions of tiny ISFET-based wells can detect these pH changes and so read the DNA sequence without optical equipment (Rothberg *et al*., 2011). This showed that ISFET arrays could be manufactured in great numbers and operated reliably.

In agriculture, ISFET-based probes are being studied for rapid measurement of soil pH and of nutrient ions such as nitrate and potassium in soil extracts. Reviews of in-field soil analysis note that such electrochemical sensors are fast and portable, but that their readings must be checked against standard laboratory tests (Adamchuk *et al*., 2004; Najdenko *et al*., 2024). ISFETs are also explored for monitoring drinking water and wastewater, for food and beverage processing, and for biomedical measurements, as summarised in Figure 2(b).

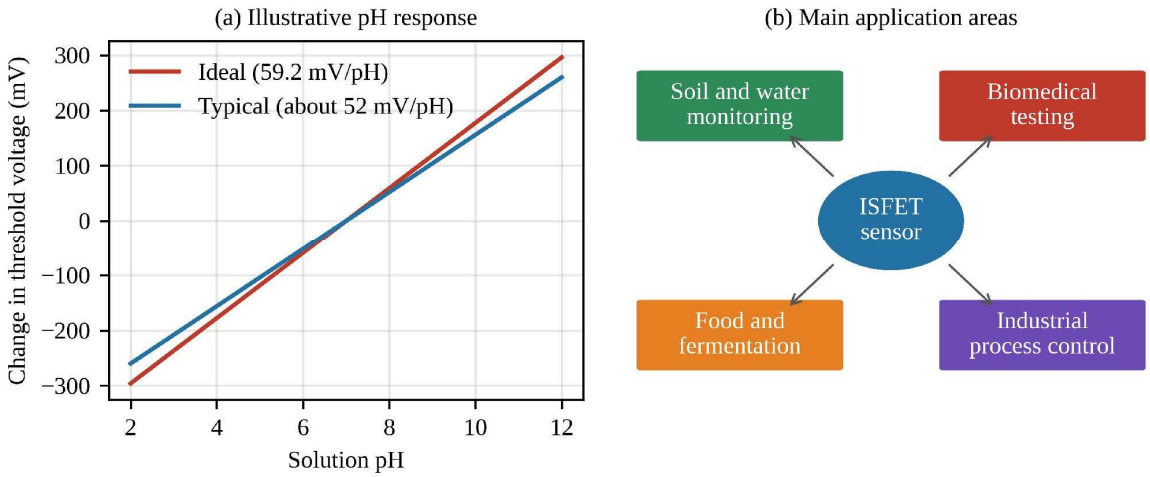



***Figure 2: (a) Illustrative pH response of an ideal and a typical ISFET (schematic, not measured data); (b) main application areas of ISFET sensors***

**Challenges**

Despite their promise, ISFETs have limitations that explain why they have not replaced older electrodes everywhere. The most commonly discussed is drift, a slow change in output even when the solution has not changed, which complicates long-term monitoring. Readings also change with temperature and can show hysteresis, meaning the output depends partly on the sensor's recent history (Bergveld, 2003; Kaisti, 2017). Some devices are sensitive to light, and membrane-based versions can respond to interfering ions that resemble the target ion.

A further difficulty is the reference electrode. A stable, miniature reference is harder to make than the transistor itself, and it often limits the size and lifetime of the complete sensor. The chip must also be packaged so that the electronics stay dry while the sensing surface remains exposed, and soil or other dirty samples can foul the surface. Regular calibration with known buffer solutions is therefore essential (Bergveld, 2003; Adamchuk *et al*., 2004).

**Future outlook**

Research is now directed at improving stability, developing better solid-state reference electrodes, and using new materials such as nanowires, two-dimensional materials, and flexible substrates to increase sensitivity (Lee *et al*., 2009; Kaisti, 2017). Combining ISFETs with temperature sensors and simple data-correction software may also reduce drift. For agriculture, the most realistic path is likely to be low-cost, regularly calibrated probes that support, rather than replace, routine laboratory soil testing.

**Conclusion**

The ISFET shows how semiconductor technology can be adapted to measure chemistry. By replacing the metal gate of a transistor with an ion-sensitive surface, it turns a change in ion concentration into a readable electrical signal. Its small size, speed, and compatibility with electronics have made it valuable in DNA sequencing and attractive for water, food, medical, and soil measurements. Drift, reference electrode design, and interference remain challenges, so careful calibration and validation against standard methods are needed. In future, improved and low-cost ISFET probes may allow farmers, water managers, and clinics to measure pH and key ions on site, making ion measurements simpler, quicker, and more widely available.

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# BEYOND THE BOTTLE: MECHANICAL BREAKTHROUGHS IN CROP PROTECTION

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## Introduction

Pests are one of the greatest challenges in agriculture, horticulture and storage systems as they directly affect crop productivity and quality. Over the years, various pest control measures have been developed, ranging from cultural and biological methods to chemical control. While chemical control gives quick results and at the same time its long term drawbacks such as insecticide resistance, environmental contamination and harm to beneficial organisms. One of the oldest and most sustainable pest management strategies is the use of mechanical control methods. Use of mechanical devices and manual forces for the destruction or exclusion of pests is known as mechanical method of pest management. Unlike chemical pesticides, mechanical methods leave no toxic residues and are safe for humans, animals and natural enemies of pests.

**Manual force methods / actions used to control pests**

| S. No. | Manual force | Target insect |
|---|---|---|
| 1. | Handpicking | Egg masses and Caterpillars |
| 2. | Beating and Swatting | Housefly and mosquito |
| 3. | Sieving | Red flour beetle |
| 4. | Winnowing | Rice weevil |
| 5. | Passing rope across rice field | To dislodge caseworm |
| 6. | Shaking neem trees | To dislodge june beetles |
| 7. | Hooking with iron hook | To remove adult rhinoceros beetle in coconut |
| 8. | Crushing | Bed bugs and lice |
| 9. | Combing | Delousing head louse |
| 10. | Brushing woolen fabrics | Cloth moth and carpet beetle |

**Mechanical force/ devices used to control pests**

| | | | |
|---|---|---|---|
| 1. | Entoletter | : | In entoleter centrifugal force is used to break the infested kernels and kill stages of storage pests while the whole grains are unaffected |
| 2. | Hopper dozer | : | It is used to kill nymphs of locusts by hording into trenches and filled with soil |
| 3. | Tillage implements | : | It is used to expose the soil borne insects (eg. Red hairy caterpillar in groundnut) |
| 4. | Mechanical traps | : | Uses of rat traps of various shapes like box trap, back break trap, wonder trap and Tanjore bow trap |

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**Mechanical exclusion methods to control pests**

Use of mechanical barriers to prevent the access of pests to hosts

| | | |
|---|---|---|
| 1. | Wrapping the fruits | Covering with polythene bag against pomegranate fruit borer |
| 2. | Banding | Banding with grease or polythene sheets on the trunk of mango to prevent mealybug |
| 3. | Netting | Used for mosquitoes and vector control in green house |
| 4. | Trenching and Digging | For trapping of marching larvae of groundnut red hairy caterpillar |
| 5. | Sand barrier | Protecting stored grains with a layer of sand on top |
| 6. | Water barrier | Protecting insect cultures against ants |
| 7. | Tin barrier | Coconut trees protected with tin band to prevent rat damage |
| 8. | Electric fencing | Low voltage electric fences used against rats |
| 9. | Alternate wetting and drying in rice field | Reduce the population of Brown plant hopper |
| 10. | Soil solarization | Involves covering of soil with transparent polythene sheets during hot summer months. Trapped solar radiation raises soil temperature (45- 55°C), killing soil borne pathogens, nematodes, weed seeds and insect eggs |
| 11. | Hot water treatment | Sugarcane setts treated at 50°C for 30 minutes helps to eliminate scale insects and mealybugs |
| 12. | Cold storage and Freezing | Freezing of fruits can eliminate fruit fly larvae |

**Appliances in controlling the pests**

| S. No. | Appliances | Uses |
|---|---|---|
| 1. | Light trap | Mostly the adult nocturnal insects are attracted towards light at night time |
| 2. | Pheromone trap | Synthetic sex pheromones are placed in traps to attract mostly males. The pheromone lure are kept in traps and are used in insect monitoring and mass trapping programmes |
| 3. | Yellow sticky trap | Cotton whitefly, aphids and hoppers prefer yellow colour. Yellow colour is painted on tin boxes and sticky material like castor oil or Vaseline is smeared on the surface. These insects are attracted to yellow colour and trapped on the sticky material |
| 4. | Blue sticky trap | Effective against thrips |
| 4. | Bait trap | In bait trap attractants are placed to attract the insect and kill those using insecticides. **Eg. Fish meal trap.** This trap is used against sorghum shootfly. Moistened fish meal is kept in polythene bag or plastic container inside the tin along with cotton soaked with insecticide to kill the attracted flies |

| S. No. | Appliances | Uses |
|---|---|---|
| 5. | Pit fall trap | Pit fall trap helps to trap insects moving on the soil surface such as ground beetles, collembolan, cut worms, termites and spiders. |

**Advantages of Mechanical control**

- Eco-friendly and safe for humans, animals and beneficial organisms
- Does not leave toxic residues on crops or in the environment
- Provides immediate reduction of pest populations
- Ideal for organic farming and IPM - based systems
- Cost - effective in small scale agriculture, kitchen gardens and nurseries

**Limitations of Mechanical control**

- Labor-intensive and time-consuming
- Not suitable for large scale commercial monoculture farming
- Requires constant monitoring and vigilance
- Only reduces pest populations, does not completely eliminate them
- Some methods (like solarization) are seasonal and cannot be applied year-round

**Conclusion**

Mechanical methods of pest control are among the oldest and most reliable practices in agriculture. They are safe, inexpensive and environment-friendly, making them particularly important in organic farming, protected cultivation and smallholder agriculture. While, they may not be practical for large-scale monoculture systems, their integration with cultural, biological and chemical methods ensures a holistic pest management strategy. Adopting mechanical control within IPM frameworks allows farmers to achieve sustainable crop protection, reduce dependence on pesticides and safeguard the environment. In the era of eco-friendly farming, mechanical pest control continues to hold significant relevance as a cornerstone of sustainable agriculture.

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# MICROPLASTICS AND SOIL MICROBES: DISRUPTING THE HIDDEN LIFE OF SOIL

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**Abstract**
Microplastics, plastic particles smaller than 5 mm, are building up in farm soils through mulch film, sewage sludge and plastic waste. Soil microbes drive nutrient cycling, residue decomposition and plant health, and they react quickly to such contamination. This article explains where microplastics in soil come from, how they alter the microbial habitat, and what is known about changes in microbial diversity, enzymes, nitrogen cycling and greenhouse gas release. Effects vary with soil, plastic type and dose, and most evidence comes from short-term laboratory studies. The article also shows how soil sensors and laboratory tests can track the biological response of soil and lists practical steps to reduce plastic inputs on farms.

**Keywords**: Microplastics, soil microbes, plastisphere, soil health, plastic mulch

## Introduction

A handful of healthy soil holds billions of bacteria, fungi and other microbes. They decompose crop residues, release nutrients, bind soil particles and help roots obtain water and nutrients. This hidden workforce now faces a new neighbour: plastic. Microplastics are plastic particles smaller than 5 mm, and nanoplastics are smaller still. Research began in the oceans, but most plastic is first produced, used and discarded on land, so terrestrial ecosystems may be at serious risk (Machado *et al*., 2018). Because microbes respond quickly to changes in their surroundings, they are among the first to show the effects (Aralappanavar and Bhatnagar, 2024).

## How does plastic reach our fields?

Mulch film, laid to conserve moisture and warm the soil, is a major source. It is thin, and removing and recycling it from fields is labour intensive and costly. Sewage sludge used as fertiliser can also carry plastic particles onto farmland, and discarded plastic breaks down slowly where it lies (Machado *et al*., 2018). Indian evidence is growing. A Toxics Link (2022) study in agricultural belts of Karnataka and Maharashtra found plastic particles at various soil depths, and the highest count, 87.57 pieces per kg of soil, came from a dumpsite in Maharashtra, almost double that of mulched soil. A later study of 40 sites in seven districts of Maharashtra reported the highest microplastic levels where plastic had been used for more than 20 years (Karwadiya and Darbha, 2025).

## How do microplastics disturb soil microbes?

Microplastics act in three ways. First, they change the habitat. Plastic particles alter soil structure, and a global meta-analysis found slower movement of the wetting front in soils containing plastic (Zhang *et al*., 2022). Second, they change soil chemistry, because organic and inorganic contaminants derived from plastics can combine to affect microbial activity (Aralappanavar and

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Bhatnagar, 2024). Third, they create a new home. The plastisphere, the microbial community living on plastic surfaces, favours plastic-degrading microbes, and both the plastisphere and plastic-contaminated soils have been reported to hold lower microbial diversity than clean soils (Aralappanavar and Bhatnagar, 2024).

**What changes in the microbial world?**

Table 1 summarises the main findings. The picture is not uniform, and responses depend on plastic type, dose and soil. A rise in enzyme activity, for example, need not signal healthier soil, since it can accompany a loss of diversity.

**Table 1: Reported effects of plastic residues and microplastics on soil microbial and related indicators**

| Indicator | Reported response | Source |
|---|---|---|
| Bacterial diversity | Lower in plastic-contaminated soil and on plastic surfaces than in clean soil | Aralappanavar and Bhatnagar (2024) |
| Soil enzyme activity | Increased by 7 to 441% across studies | Zhang *et al*., (2022) |
| Nitrogen-related microbes | More nitrogen-fixing and phosphorus-solubilising bacteria; fewer nitrifiers and ammonia oxidisers | Aralappanavar and Bhatnagar (2024) |
| Greenhouse gases | Carbon dioxide and nitrous oxide release stimulated; effect on methane inconclusive | Chen *et al*., (2025) |
| Soil water and nutrients | Wetting-front movement down by 10 to 14%, dissolved organic carbon by 9%, total nitrogen by 7% | Zhang *et al*., (2022) |
| Plant growth | Plant height down by 13%, root biomass down by 14% | Zhang *et al*., (2022) |

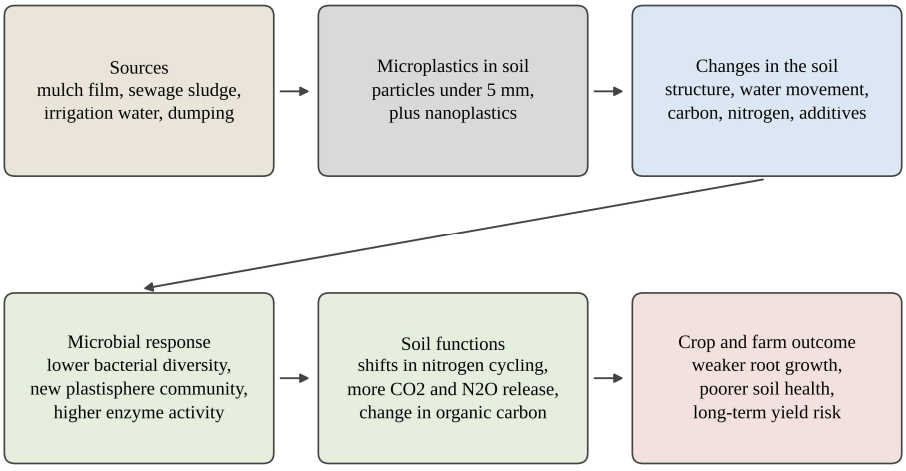



***Figure 1: From plastic source to farm outcome, a simplified chain of effects on soil microbes***

**Why does it matter for crops and climate?**

Microbes control the nitrogen and carbon that crops and the climate depend on. More nitrogen fixers but fewer nitrifiers can change how nitrogen is supplied to plants, and stimulated carbon

dioxide and nitrous oxide release adds to greenhouse gas emissions (Aralappanavar and Bhatnagar, 2024; Chen *et al*., 2025). Smaller root biomass adds a direct cost to crops (Zhang *et al*., 2022). Figure 1 shows the chain of events. Most reports, however, come from short-term laboratory experiments, so field studies under different soil types and agro-climatic conditions are needed (Aralappanavar and Bhatnagar, 2024).

**Can sensors help us watch the soil?**

Standard methods for measuring microplastics in soil are still lacking (Machado *et al*., 2018), so what farmers and advisers can track is the soil's response. Soil carbon dioxide efflux, the release of carbon dioxide from the soil surface, is a proxy for respiration. It reflects root and microbial activity but does not directly measure microbial biomass or diversity. Chip-based ion-selective field-effect transistor (ISFET) sensors convert ion concentration into an electrical signal and can measure pH and ions such as nitrate, ammonium and potassium (Bergveld, 2003). Such electrochemical sensors are fast and portable, but drift, interfering ions and fouling mean that regular calibration and checks against laboratory tests are essential (Adamchuk *et al*., 2004; Najdenko *et al*., 2024). Spectroscopy can estimate soil organic carbon from reflected light, but only after calibration with laboratory-measured samples (Viscarra Rossel *et al*., 2011). A changed reading does not prove that plastic is the cause. Sensors are best used to flag fields for closer study, alongside laboratory tests of microbial biomass, enzymes and community composition.

**What can farmers do?**

The surest step is to reduce plastic entering the soil. Farmers can lift and dispose of mulch film properly after each crop instead of leaving or burying fragments, and keep plastic waste from being dumped near fields. Toxics Link (2022) also calls for better disposal systems and machinery to recover residual film. Where suitable, organic mulches can replace plastic, and the source of any sludge applied to fields should be known. Extension services and soil-testing laboratories can support this with local field trials.

**Conclusion**

Microplastics are an emerging stress on the microbes that keep soil fertile. Current evidence shows lower bacterial diversity, shifted nitrogen-related groups, higher enzyme activity, more greenhouse gas release and weaker root growth, although results differ among soils and plastics. Long-term field studies in Indian soils are the next need. Affordable, regularly calibrated sensors combined with routine laboratory testing may soon let farmers and advisers monitor soil biological health, but cutting plastic use and waste on farms remains the most dependable protection for the hidden life of soil.

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# MICROPROPAGATION IN ORCHIDS: FROM LABORATORY TO INDUSTRIAL-SCALE PROPAGATION

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**Abstract**
Orchids hold significant economic and ecological value in global floriculture, yet their propagation faces inherent biological constraints—minute seeds lacking endosperm require specific mycorrhizal symbiosis for germination, while conventional division is slow and inefficient. Micropropagation has emerged as a transformative solution for large-scale propagation, germplasm conservation, and endangered species protection. This article reviews the core pathways of orchid micropropagation, including protocorm-like body (PLB) formation, somatic embryogenesis, and organogenesis, with attention to the molecular mechanisms distinguishing PLBs from true somatic embryos. It examines optimization strategies for culture media, highlighting the role of natural additives such as banana homogenate, coconut water, and pineapple extract in reducing costs and enhancing regeneration efficiency, alongside the critical balance of cytokinins and auxins. Technological advances in temporary immersion systems are discussed for their superior gas exchange and nutrient supply. The article further addresses acclimatization and transplanting protocols that determine field survival, the dual commercial and conservation value of the technology, and persistent challenges including somatic clonal variation and hyperhydricity. Future directions involving bioreactor technology, gene editing, and transcriptome analysis are considered, underscoring micropropagation as an indispensable tool for both the orchid industry and orchid diversity conservation.

**Keywords:** Orchidaceae; micropropagation; protocorm-like bodies; organogenesis; acclimatization

## Introduction

Orchids occupy a pivotal position in the international floriculture market, prized for their distinctive floral morphology, rich color diversity, and long-lasting blooms. Orchidaceae is one of the largest families of flowering plants, known for colourful and fragrant flowers. Orchids show great diversity in size, shape, colour and flower structure. However, sexual reproduction in orchids faces a fundamental obstacle: their seeds are extremely minute, lacking endosperm and cotyledons or other nutrient-storing structures. Under natural conditions, they must rely on symbiotic relationships with specific mycorrhizal fungi to germinate—a process that often takes months or even years. Traditional division propagation is inefficient and cannot meet the commercial production demand for large quantities of high-quality seedlings. The emergence of micropropagation technology has provided a practical and feasible solution for the large-scale propagation, germplasm conservation, and endangered species protection of orchids. Knudson in

1922, discovered that orchid seeds can germinate in vitro on a simple sugar-containing medium without fungi. Tissue culture/micropropagation allows rapid production of large numbers of uniform, true-to-type and virus-free plants under controlled conditions. Meristem and shoot-tip cultures are widely used, especially for commercial orchid propagation. Micropropagation is commercially used in orchids such as *Cymbidium*, *Dendrobium*, *Oncidium*, *Phalaenopsis*, *Vanda*, etc.

**Core Pathways of Orchid Micropropagation**

After decades of development, the technical system for orchid micropropagation has formed several relatively mature technical routes. Among these, the protocorm-like body (PLB) pathway is the most characteristic propagation method for orchids. Protocorm-like bodies are structures unique to orchid tissue culture, morphologically resembling the protocorms formed during seed germination but originating from somatic tissues, with the capacity for rapid proliferation and regeneration into complete plants. Research indicates that PLB formation follows a developmental program independent of somatic embryogenesis—in *Phalaenopsis*, STM and KNOX-class genes play key roles in PLB regeneration, while embryo-specific genes such as *LEC1*, *BBM*, and *FUS3* are not expressed (Fang, 2025, Aghaei *et al.,* 2026). This confirms at the molecular level that PLBs are not true somatic embryos. Somatic embryogenesis is another important pathway. Recent studies have shown that in direct somatic embryogenesis from *Phalaenopsis* leaf explants, thidiazuron (TDZ) plays a critical inducing role. When TDZ concentration is 5 mg/L, the somatic embryo formation rate reaches 32%, and embryo maturation time is shortened to 37 days after culture initiation. These results provide quantitative evidence for optimizing the somatic embryogenesis pathway in orchids. The organogenesis pathway induces adventitious shoot formation directly through explants such as shoot tips, peduncle nodes, and leaves. For orchids with pseudobulbs such as *Dendrobium*, stem nodes are an ideal explant source. Under the synergistic action of BA and NAA, axillary buds from stem nodes can be efficiently induced to germinate and form complete plants. Peduncle node culture is particularly widely applied in commercial propagation of *Phalaenopsis*, as the explant collection does not affect mother plant growth and contamination rates are relatively low (Sarmah *et al.,* 2024).

**Optimization Strategies for Culture Media and Exogenous Additives**

The culture medium system for orchid micropropagation is based on Murashige and Skoog (MS) medium, but different genera and species have significantly different nutritional requirements. In recent years, the application of natural complex additives has become an important direction for reducing costs and improving efficiency. Knudson C media is specifically used for orchids micropropagation. Banana homogenate, coconut water, potato extract, and pineapple juice are rich in amino acids, vitamins, and natural growth-regulating substances, and can effectively replace or reduce the use of synthetic hormones. Explant such as shoot tips, leaf segments, pseudobulbs, ariel roots, floral part are effective for micropropagation in orchid.

Research data show that in the micropropagation of *Laelia rubescens* and *Encyclia citrina*, Knudson-C medium supplemented with 90 g/L banana pulp under 24-hour light conditions achieved the highest number of seedling formations. For *Cattleya*, banana powder-supplemented medium significantly increased shoot formation, with the two-spike variety reaching a maximum of 98.17 shoots per flask. In the micropropagation of *Cattleya* rex, treatment with 12.5 g pineapple extract shortened PLB formation time to 21.1 days, with 100% PLB formation at 30 days. These natural additives not only provide nutrients and growth-regulating substances but also significantly reduce medium costs, which is of great economic significance for commercial production.

The ratio of plant growth regulators is another key to successful micropropagation. The balance between cytokinins and auxins determines the developmental direction of explants. Cytokinins like BAP, Kinetin, Picloram; Auxins like NAA, IAA, IBA are used for shooting and rooting respectively. pH of the medium is adjusted to 5.8 and sterilized by autoclaving at 121°C for 20 min. both semi-solid and liquid media can be used. For semi-solid media agar @ 0.8% is added. Culture conditions: Temperature: 25 ± 2°C and Relative Humidity: 50–60%. For *Dendrobium bensoniae* a combination of BAP (0.5 mg/L) + IBA (1.0 mg/L) was effective for rooting. Low auxin concentration is generally better than high concentration for developing a good root system (Longchar and Deb, 2022). In *Phalaenopsis* tissue culture, 1/2 MS medium supplemented with 2.5 mg/L BAP, 0.1 mg/L NAA, and 15% coconut water achieved optimal regeneration with 5.22 shoots, 9.07 leaves, and 3.60 roots per explant. For *Paphiopedilum gratrixianum*, the optimal combination for seed germination was 1.0 mg/L $GA_3$ + 1.0 mg/L BAP, while PLB formation was best with 1.0 mg/L $GA_3$ + 0.5 mg/L BAP.

**Technological Evolution of Culture Systems**

Although traditional semi-solid culture systems are easy to operate, they suffer from limited gas exchange and uneven nutrient gradients. Temporary immersion systems effectively improve nutrient supply and gas exchange by periodically immersing explants in liquid medium. In the micropropagation of *Cymbidium finlaysonianum*, the use of the RITA® temporary immersion system increased PLB weight by 18.7-fold and regenerated 84.6 shoots. This technology has significant advantages for large-scale commercial propagation, especially when rapid multiplication of valuable varieties or endangered species is required.

**From Laboratory to Field: Acclimatization and Transplanting**

The ultimate success of micropropagation depends on whether tissue-cultured plantlets can successfully adapt to the natural environment. Acclimatization of orchid plantlets requires gradual reduction of humidity, increased light, and selection of suitable substrates. Studies show that a substrate of garden soil, cocopeat, and charcoal at 1:1:1 achieved 100% transplant survival for *Aerides crispa*. For *Paphiopedilum gratrixianum*, a 1:1 mixture of vermiculite and charcoal as acclimatization substrate achieved 93.89% survival. As possible alternatives Brick: Coal: Sawdust: Peat Moss in 1:1:1:0.5 ratio can also be used. The core requirements for acclimatization substrates are good aeration and moderate water retention to promote new root establishment and adaptation of microbial communities.

**Dual Value of Commercialization and Conservation**

The economic value of orchid micropropagation technology is reflected at multiple levels. The global orchid industry has an annual output value exceeding 500 million USD, with the Dutch *Phalaenopsis* market reaching 422 million euros and 117 million plants sold in 2020 alone. Micropropagation technology makes rapid propagation of new varieties possible, significantly shortening the cycle from laboratory to market. At the same time, for endangered orchid species, micropropagation technology provides an effective means of ex situ conservation. Through asymbiotic seed germination and PLB proliferation, artificial populations can be established without excavating wild plants, providing materials for reintroduction and germplasm resource conservation (Shang *et al.,*2025).

**Conclusion and Prospects**

Modern propagation and production technology has made orchids accessible to a much broader section of the society. The fact that all major commercial tissue culture laboratories in the world are

involved in orchid micropropagation emphasizes how popular these flowers have become. Development of new hybrids and their commercial cultivation have now become a lucrative industry in many countries of the world. The rising popularity of orchids has created a demand for high quality plant materials. Although orchid micropropagation technology is quite mature, it still faces several challenges. Somatic clonal variation is a potential risk in long-term subculture, which may lead to genetic instability of regenerated plants. Molecular marker-assisted monitoring of genetic stability should become a routine step in commercial production. In addition, the response of different orchid genera and species to culture media and hormones varies greatly, and the lack of a "universal" protocol means that micropropagation of each new species requires independent optimization experiments.

Looking ahead, the popularization of bioreactor technology will further enhance propagation efficiency, while the combination of gene editing and transcriptome analysis is expected to reveal the molecular regulatory networks underlying orchid regeneration capacity, providing theoretical guidance for precise optimization of culture conditions. Against the backdrop of climate change and habitat loss, micropropagation technology is not only a pillar of the orchid industry but also an indispensable tool for the conservation of orchid diversity.

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# APPLICATIONS OF MIXED LEVEL FRACTIONAL DESIGNS IN GREENHOUSE EXPERIMENTS

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**Abstract**
Agricultural researchers often need to study factors that naturally have different numbers of levels, such as four varieties, three irrigation schedules, five fertilizer doses and two biofertilizer treatments. A complete factorial experiment can then become too large for available land, labour and inputs. Mixed-level fractional factorial designs offer a practical alternative by selecting a smaller, carefully balanced set of treatment combinations. This popular article explains their field-level value through two planning examples and describes how the R package MixFrac helps generate economical designs, check balance and near-orthogonality, identify aliasing among effects and arrange runs to reduce time or spatial trends. Used with sound agronomic judgement, blocking and suitable replication, the approach can make early-stage screening faster, cheaper and more informative.

**Keywords:** Agricultural screening; Mixed-level design; Fractional factorial; MixFrac

## Introduction

Modern agricultural experiments rarely involve factors with the same number of options. A breeder may compare four varieties, an agronomist may test three irrigation schedules, fertilizer may be applied at five doses and a microbial input may have only two treatments. This unequal-level structure is scientifically natural, but it creates a practical problem: the number of treatment combinations multiplies very quickly. In a full factorial experiment, every level of every factor is combined with every level of the other factors. This is statistically attractive, but it may demand more plots than the research farm, greenhouse or laboratory can support. Fractional factorial designs address this problem by selecting an informative subset of combinations. The aim is not simply to reduce runs; it is to reduce them while keeping factor levels well represented and while controlling the extent to which important effects are mixed or “aliased” with one another.

## Why mixed-level fractional designs matter in agriculture

These designs are most useful during screening, when the researcher wants to identify influential factors and promising treatment regions before committing resources to a larger confirmatory trial. They can be applied in crop management, horticulture, soil fertility, protected cultivation, post-harvest technology, animal nutrition, food processing and agricultural engineering. The greatest benefit is obtained when many candidate factors are under consideration but only a limited number of experimental units are available.

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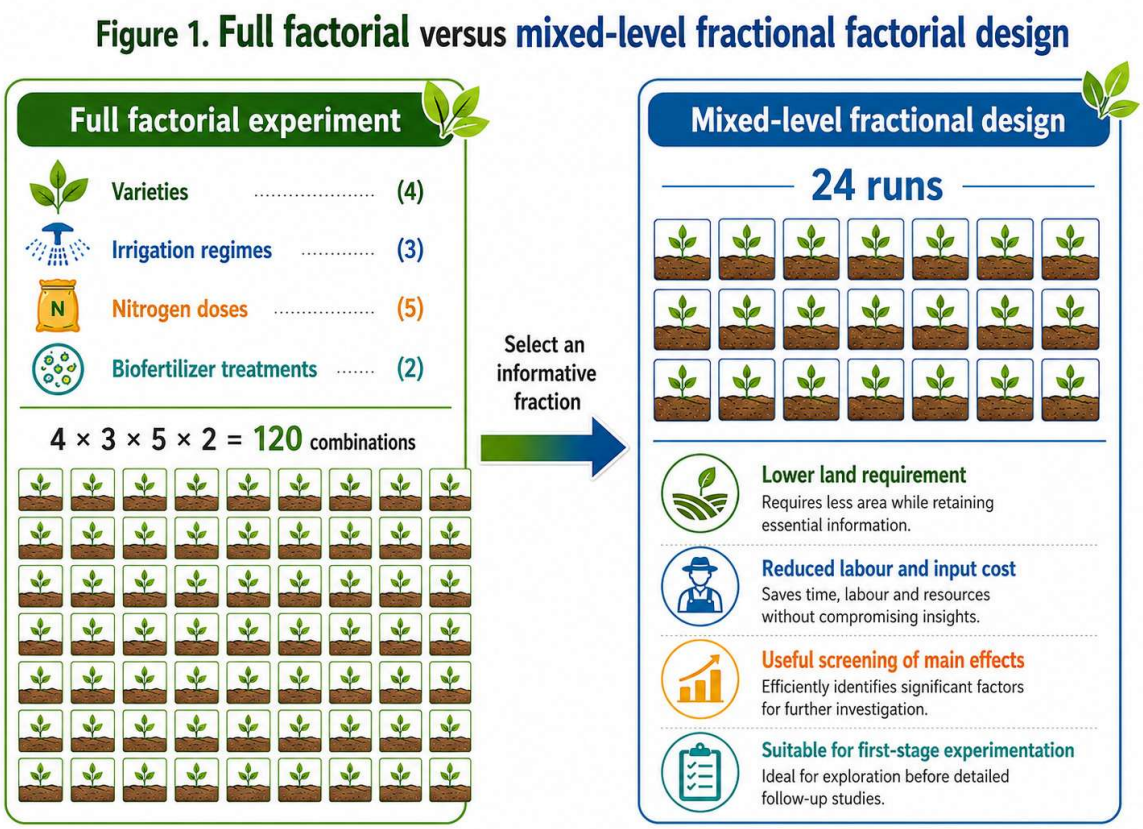
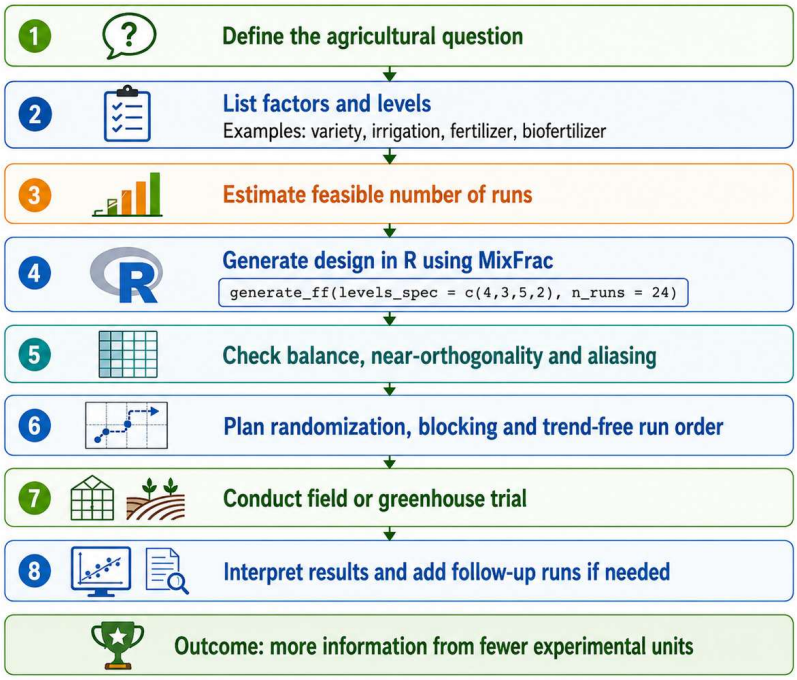



**Table 1. Two agricultural planning examples for mixed-level fractions**

| Example | Factors and levels | Full combinations | Illustrative fraction | Main purpose |
|---|---|---|---|---|
| 1 | 4 varieties × 3 irrigation regimes × 5 nitrogen doses × 2 biofertilizer treatments | 120 | 24 runs | Broad crop-input screening |
| 2 | 2 seed-priming methods × 3 irrigation intervals × 4 nutrient concentrations | 24 | 12 runs | Nursery or greenhouse screening |

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**Figure 2.** Practical workflow for using mixed-level fractional designs in agricultural research




**Example 1: Screening crop varieties and input-management options**

Consider an early-stage cereal experiment with four crop varieties, three irrigation regimes, five nitrogen doses and two biofertilizer treatments. The complete factorial requires 4 × 3 × 5 × 2 = 120 treatment combinations. Before replication, blocking and border rows are added, this is already too large for many research stations.

An illustrative 24-run fraction uses only one-fifth of the full treatment space. Variety, irrigation and biofertilizer can each be represented equally often. Nitrogen cannot be perfectly balanced across five levels in 24 runs, but it can be made optimally near-balanced, with level counts differing by no more than one. Under a main-effect screening model, the design can compare all four factors while leaving residual degrees of freedom for error assessment. The practical value is straightforward: the research team can identify varieties or input levels that show strong average effects and can flag a few potentially important interactions for follow-up. However, the 24-run fraction is not intended to estimate every possible interaction independently. It should be viewed as a first-stage decision tool that helps select treatments for a larger replicated and blocked experiment.

**Example 2: A compact nursery or greenhouse trial**

Suppose a nursery study examines two seed-priming methods, three irrigation intervals and four nutrient concentrations. A complete 2 × 3 × 4 experiment needs 24 treatment combinations. When only 12 trays, benches or controlled-environment units can be handled at one time, a 12-run mixed-level fraction can halve the experimental load. A good fraction spreads the levels of each factor as evenly as possible and avoids repeatedly pairing the same levels. The resulting trial can reveal whether priming, irrigation or nutrient concentration deserves priority in the next phase. If the package reports strong aliasing between a main effect and an interaction that is biologically plausible, the researcher can add a small number of targeted runs rather than repeating the entire experiment.

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**The role of the R package MixFrac**

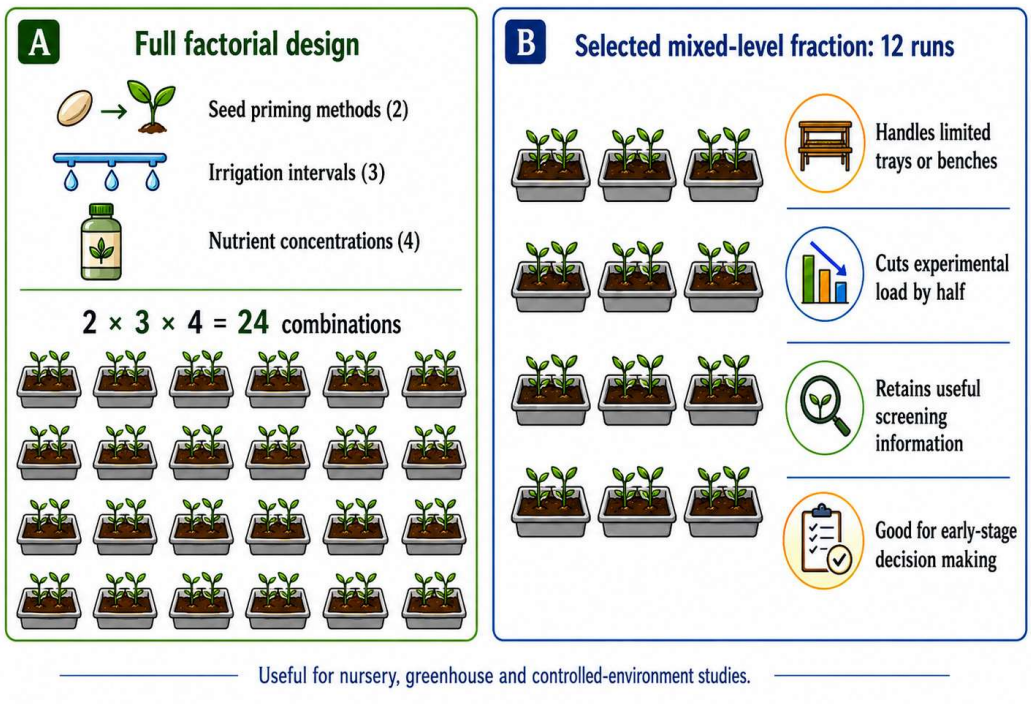
MixFrac (Das, 2025) converts the design principles into an accessible and reproducible workflow. The user provides the number of levels for each factor and the desired number of runs. The package then constructs a regular fraction when an appropriate equal-level structure exists or searches for an efficient mixed-level fraction when the factors have unequal levels. Its main function, generate_ff(), can return the design, diagnostics and an optional trend-free run order. For the four-factor crop-input example, the package can be installed from CRAN and asked to generate a 24-run fraction. The following command requests the design and its main diagnostics:

```
install.packages("MixFrac")
library(MixFrac)

crop_design <- generate_ff(
  levels_spec = c(4, 3, 5, 2),
  n_runs = 24,
  max_int_order = 3,
  alias_min_abs_corr = 0.90,
  parts = c(1, 2),
  tf = FALSE,
  verbose = TRUE)
```

The same function can be used for the smaller 2 × 3 × 4 example by changing levels_spec to c(2, 3, 4) and n_runs to 12. When tf = TRUE, the package can also produce a deterministic trend-free order, which is valuable when runs are performed over time or along a greenhouse bench where gradual trends may occur.

**Figure 3. Compact nursery or greenhouse screening using a mixed-level fraction**



**How to use the output responsibly**

- Start with an agronomically meaningful question. Software cannot decide which varieties, doses or treatment ranges are scientifically sensible.
- Use fractional designs mainly for screening. Important conclusions should be confirmed through appropriate replication, randomization and blocking.
- Examine alias information before interpreting interactions. A large correlation between model terms means that the observed pattern may not belong to one effect alone.
- Match the run order to the field situation. Trend-free ordering can help, but spatial blocking is still needed when fertility gradients or other field heterogeneity are expected.
- Plan sequentially. When a promising effect is partially confounded, add a few targeted runs to clarify it rather than automatically expanding to the full factorial.

**Conclusion**

Mixed-level fractional factorial designs provide a realistic bridge between statistical completeness and agricultural feasibility. They allow several unequal-level factors to be screened with fewer plots, trays or laboratory units while preserving useful balance and interpretability. In the illustrative crop-input example, a 24-run fraction replaces an initial 120-combination full factorial; in the nursery example, 12 runs replace 24 combinations. The R package MixFrac makes this approach easier to implement by constructing designs, assessing balance and near-orthogonality, reporting aliasing and producing trend-free run orders. Its greatest value is not merely saving runs, but helping researchers use limited resources in a planned, transparent and reproducible manner.

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# MUDSKIPPERS: THE FISH THAT WALK ON LAND

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## Introduction

Mudskippers are fascinating amphibious fishes belonging to the subfamily Oxudercinae of the family Gobiidae. They are widely distributed in tropical and subtropical coastal regions, particularly in mangrove forests, estuaries, and intertidal mudflats. Unlike most fishes, mudskippers exhibit unique adaptations that enable them to move on land and remain out of water for extended periods under suitable environmental conditions. These fishes possess several morphological, physiological, and behavioural adaptations, including muscular pectoral fins for terrestrial locomotion, elevated eyes for effective vision, and the ability to respire through their skin and the lining of the buccopharyngeal cavity when these surfaces remain moist. Such characteristics make mudskippers important subjects for understanding amphibious adaptations and the evolutionary transition between aquatic and terrestrial environments.

Mudskippers also play a significant ecological role in coastal ecosystems through their feeding, burrowing, and interactions with other organisms. However, habitat degradation, mangrove destruction, and coastal pollution may affect their populations and habitats. Therefore, understanding their biological characteristics, ecological importance, and environmental adaptations is essential for further research and the conservation of coastal ecosystems.

**Taxonomical Classification of Mudskippers**

| Taxonomic Category | Classification |
|---|---|
| Kingdom | Animalia |
| Phylum | Chordata |
| Subphylum | Vertebrata |
| Class | Actinopterygii |
| Order | Gobiiformes |
| Family | Gobiidae |
| Subfamily | Oxudercinae |
| Genus | *Periophthalmus* |
| Species | *Periophthalmusargentilineatus* |
| Common name | Barred Mudskipper |

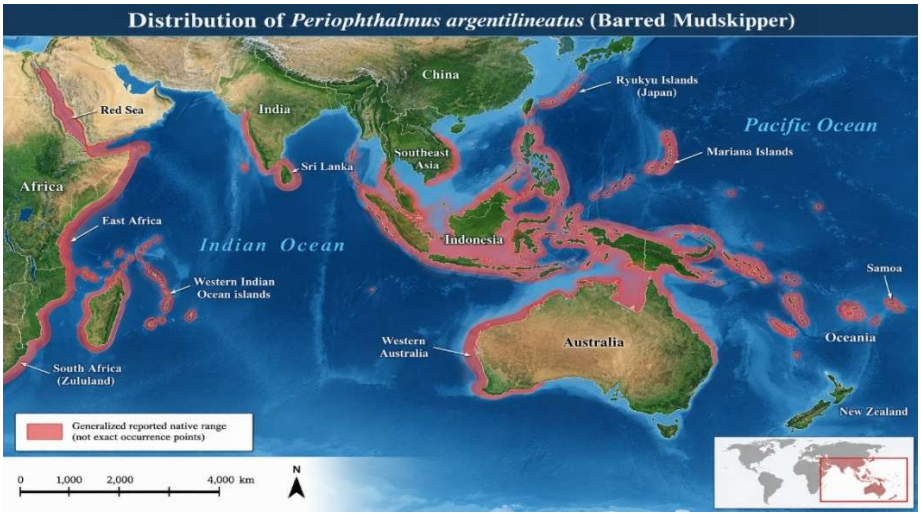
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*Periophthalmus argentilineatus*

**Distribution**

*Periophthalmus argentilineatus*, commonly known as the barred mudskipper, is widely distributed throughout the Indo-West Pacific region. Its geographical range extends along the eastern coast of Africa, from South Africa northwards to the Red Sea, including several islands in the western Indian Ocean. Towards the east, it occurs in regions extending to the Mariana Islands and Samoa, while its distribution extends northwards to the Ryukyu Islands and southwards to western Australia and other parts of Oceania.This species primarily inhabits tropical coastal environments, particularly mangrove forests, estuaries, and intertidal mudflats. It is commonly associated with brackish-water habitats but may also occur in freshwater and marine environments.




**Distinctive Characters**

*Periophthalmus argentilineatus*, exhibits several distinctive morphological and behavioural characteristics that enable it to survive in intertidal environments. Its elongated body, prominent eyes positioned on the upper surface of the head, and muscular pectoral fins facilitate vision and locomotion on muddy substrates. The species is characterized by distinctive dark vertical bars on its body, which help distinguish it from other mudskippers. It can remain out of water for extended periods under suitable conditions by utilizing cutaneous and buccopharyngeal respiration, provided that these surfaces remain moist. Its ability to move across mudflats, climb over small obstacles, and tolerate fluctuations in environmental conditions makes it a well-adapted amphibious fish of mangrove ecosystems.

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**Behaviour**

*Periophthalmus argentilineatus*, exhibits distinctive amphibious behaviour, spending considerable time on exposed mudflats during low tide. It moves on muddy substrates using its muscular pectoral fins and tail. The species displays territorial behaviour, particularly among males during courtship and competition for resources. It feeds mainly on small invertebrates and other available food organisms found in mudflat habitats. Mudskippers also construct or occupy burrows in the substrate, which provide shelter and may serve as breeding sites. Their ability to tolerate periodic exposure to air and changing tidal conditions enables them to survive in dynamic intertidal environments.





**Food and Feeding Behaviour**

*Periophthalmus argentilineatus* is a predominantly carnivorous, bottom-dwelling fish that feeds mainly on small invertebrates found in intertidal mudflats and mangrove ecosystems. Its diet includes copepods, amphipods, polychaete worms, small crabs, and insects. Feeding habits vary with body size, with smaller individuals consuming tiny crustaceans, while larger individuals tend to feed on polychaetes and mangrove crabs.

This species commonly forages on exposed mudflats during low tide, using its well-developed eyes to locate prey on the muddy substrate. Its amphibious lifestyle enables it to exploit terrestrial and intertidal food resources that may be inaccessible to many fully aquatic fishes. Its feeding patterns are influenced by prey availability, habitat conditions, and body size, making it an important predator in mangrove food webs.

**Life cycle**

The life cycle of *Periophthalmus argentilineatus* involves several developmental stages, beginning with eggs and progressing through larval, juvenile, and adult stages. Spawning generally occurs in burrows constructed in intertidal mudflats, where the eggs develop under suitable environmental conditions. After hatching, the larvae enter the planktonic phase and remain in the water column, where they feed on microscopic organisms. As they grow, the larvae gradually develop the morphological characteristics required for an amphibious lifestyle. Juveniles subsequently settle in suitable coastal habitats, including mangrove ecosystems and muddy intertidal zones. Adults attain sexual maturity and reproduce, thereby completing the life cycle. The duration of each developmental stage may vary depending on environmental conditions, food availability, and reproductive factors.

**Ecological Relationships and Ecosystem Functions**

Mudskippers play an important ecological role in intertidal mudflat and mangrove ecosystems through their feeding activities, trophic interactions, and burrowing behaviour. Their diet may include benthic algae, diatoms, detritus, crustaceans, insects, and other small organisms, depending on the species and habitat. By consuming these food resources, mudskippers participate in food-web dynamics and contribute to the transfer of energy between benthic and terrestrial–aquatic

food webs. They may also serve as prey for larger predators, although the importance of this role varies among habitats. Furthermore, mudskippers construct and occupy burrows in intertidal sediments, which provide shelter and, in some species, sites for reproduction. Their burrowing and sediment-disturbing activities may influence local sediment conditions and associated microbial processes; however, the extent to which mudskippers directly regulate nutrient cycling requires further species-specific investigation (Shojaei *et al*., 2022).

**Exploitation and Threats**

*Periophthalmus argentilineatus* may be harvested for local consumption, subsistence fishing, and use as bait in some coastal communities. However, the extent of its commercial exploitation varies across its geographical range. The major threats to this species include mangrove destruction, coastal development, habitat degradation, water pollution, and changes in land use. Reclamation of intertidal mudflats and alterations to natural tidal flows can also affect its feeding, breeding, and burrowing habitats. Furthermore, climate change and rising sea levels may modify coastal habitats and influence the distribution of suitable intertidal environments. Protecting mangrove forests and maintaining healthy mudflat ecosystems are essential for conserving this species and the biodiversity associated with its habitats.

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# STRIPED MURREL (*Channa striata*): BREEDING AND SEED PRODUCTION TECHNIQUES

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## Introduction

In India, striped murrel (*Channa striata*) is a high-value freshwater food fish prized for its taste, nutritional value and market demand, offering promising opportunities for aquaculture, rural livelihoods and sustainable fish seed production. In Malaysia, people believe that eating snakehead hastens wound healing, and its flesh is rich in arachidonic acid, a precursor of chemicals involved in blood clotting and tissue repair (Wan Yaakob & Ali, 1992). The fish is also nutritious, with about 25.2 g of protein per 100 g of flesh (Hidayat & Amelia, 2020). Intensive fishing has reduced wild populations of the striped snakehead (Hidayat & Amelia, 2020). Farmers interested in murrel culture face a major challenge due to the limited availability of quality fish seed. Difficulties in achieving consistent captive breeding restrict seed production and hinder the expansion of murrel aquaculture (Francis *et al*., 2000).

## Biology and Natural Breeding Behaviour

Murrel is an air-breathing fish. It survives in shallow, muddy, low-oxygen waters where most fish would struggle, which is a big advantage for farming (Hidayat & Amelia, 2020; Paray *et al*., 2013). In the wild it spawns at the start of the rainy or monsoon season. When the water level slowly rises, the pair builds a nest near water hyacinth in shallow water with a weak current, and a female may spawn two to three times in a season (Hidayat & Amelia, 2020). In India, mature breeders are seen from May to October, although in southern India they can be found round the year. Sexes are separate, so careful examination is needed to judge maturity.

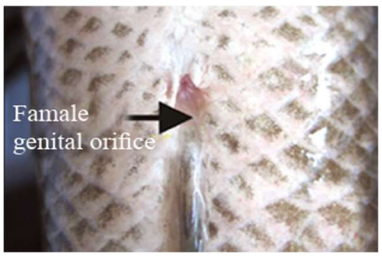
## Broodstock Selection

Healthy, lively, free of wounds and gonad-mature broodstock should be selected for breeding. In concrete-tank trials in Yogyakarta, Indonesia, breeders were 8 to 12 months old and weighed 150 to 200 g (Hidayat & Amelia, 2020). In Tamil Nadu, workers have used larger fish: 1 to 2 kg fish in earthen ponds (Francis *et al*., 2000). In Malaysia, juveniles of 15 to 20 cm took five to six months to mature in tanks (Wan Yaakob & Ali, 1992).

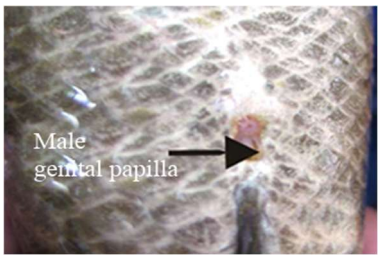
## Sex Identification

- Female: a slightly bulging belly, a round, reddish vent and a visible genital pore. Eggs ooze out if the belly is gently pressed.
- Male: a slimmer body, a pale, slit-like vent and a pointed anal papilla. The male never oozes eggs (Paray *et al*., 2013).

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Female genital pore




Male genital pore & papilla



A single egg mass

***Source: Rawat et al., (2020)***

**Broodstock feeding**

In Indonesia, broodfish were fed 4 mm pellets (44 to 46% protein) twice a day (Hidayat & Amelia, 2020). In Tamil Nadu, murrel were fed squid waste at 5% of body weight daily (Francis *et al*., 2000). A suitable package of diets using chicken intestine (70% protein) followed by fish waste (56% protein) and beef liver (63% Protein) was suggested for a maximum spawning of more than 6000 eggs with 90% fertilization and hatching. Chicken intestine was recommended as a suitable diet for brood fish.

**Natural Breeding: Simulating Monsoon Conditions**

The "backyard method" developed at Universiti Sains Malaysia (Wan Yaakob & Ali, 1992). It needs no hormones, no injections and no expensive equipment.

- ✓ Set up the tank: Use concrete tanks of about 3.0 x 1.5 x 1.2 m. Stock about 20 fish per tank and feed them minced trash fish. Keep the water shallow (about 15 cm) with half the surface covered by water hyacinth.
- ✓ Add a gentle flow: Let in 0.5 to 1.0 litre of water per second and add a culture of zooplankton (*Moina*) as the first food for the future larvae.
- ✓ Simulate the flood: Next day, suddenly raise the water to about 45 cm and hold it there. The fish spawned between the second and fourth day after the water level change.
- ✓ Stop the flow: once spawning starts, so the eggs are not washed down the drain.

Spawning happens at night or early morning. The male chases and encircles the female, bends his body close to hers and fertilises the eggs as they are released (Wan Yaakob & Ali, 1992; Hidayat & Amelia, 2020). The eggs are float and get trapped among the hyacinth roots. Check the ponds quietly each morning. Fertilised eggs turn translucent or pale yellow and soon show black spots, while unfertilised eggs turn opaque white (Hidayat & Amelia, 2020; Wan Yaakob & Ali, 1992). The Malaysian method gave about 5,000 to 10,000 eggs per pair and very high hatching (Pair 1-97.9% and Pair 2-64.4%) (Wan Yaakob & Ali, 1992).

Similar natural spawning in 3 x 3 x 1 m concrete ponds, with water hyacinth and pieces of pipe as hiding places, one male and one female per pond, gave a fertilisation rate of 92% and a hatching rate of 94% in Indonesia (Hidayat & Amelia, 2020).

**Hormone-Induced Breeding Techniques**

Sometimes farmers need fish to spawn on a fixed schedule. Then hormone injection helps.

| Source | Hormone | Female | Male | Description |
|---|---|---|---|---|
| ICAR-CIFA (Kumar, n.d.) | HCG | 2000 IU/kg | 1500 IU/kg | Spawning then occurs in 16 to 18 hours at 26-28°C |
| | Carp pituitary gland extract | 20-30 mg/kg | 10-20mg/kg | |

| Source | Hormone | Female | Male | Description |
|---|---|---|---|---|
| | Ovatide/Ovaprim | 0.6 ml/kg | 0.4 ml/kg | |
| Paray *et al*., (2013) | HCG | 6000 IU/kg – both sexes were injected | | Fish became active about 6 hours later and spawned about 26 hours later |
| Wan Yaakob & Ali (1992) | HCG | 5000 IU/kg – both sexes were injected | | - |

According to ICAR-CIFA, a female can yield 10,000 to 15,000 eggs per kg body weight at a time, with 70 to 95% fertilisation, and may spawn 3 to 4 times a year.

**Parental Care, Egg Development and Hatching**

After spawning, do not rush to remove the breeders. The fish stay with the eggs, circle beneath them and fan them with their pectoral fins. The male is usually the more vigilant guard, though both parents may share the job (Paray *et al*., 2013; Wan Yaakob & Ali, 1992). Eggs guarded by the parents remained clean, developed well and reached the post-larval stage with high survival. Parental care also protects eggs from fungal infection and predators and raises the hatching rate (Paray *et al*., 2013).

Eggs hatch in roughly a day to two days, depending on temperature and aeration (Hidayat & Amelia, 2020; Wan Yaakob & Ali, 1992; Paray *et al*., 2013).

| Source | Hatching time | Hatching rate |
|---|---|---|
| ICAR-CIFA (Kumar, n.d.) | 22-24 hours, with the yolk sac used up in about 72 hours | 70-95% |
| Paray *et al*., (2013) | 24 hours after spawning | - |
| Wan Yaakob & Ali (1992) | 28 hours after spawning | Natural-97.9% and 64.4%<br>HCG-53.2% and 56.4% |

**Larval Rearing and Early-Stage Nutrition**

The hatchlings (2.8mm – 3.2mm) are dark and guarded by the parents especially by the male parent. After 2 weeks, the fry are removed from the breeding tanks to avoid cannibalism.

| Stage or age | Feed | Source |
|---|---|---|
| Day 1-3 | No feed, live on the yolk sac | Hidayat & Amelia (2020) |
| Day 3-10 | Zooplankton like *Moina*, rotifer or *Artemia* nauplii as much as they eat | Wan Yaakob & Ali (1992) and |
| Day 3-17 | Tubifex worms | Hidayat & Amelia (2020) |
| Day 3-20 (Fry rearing in outdoor tanks) | Aquatic insects, tubifex, chopped earthworms mixed with powdered fish meal and soya flour (3:1) @ 5 to 10% of body weight | ICAR-CIFA (Kumar, n.d.) |
| Day 15-20 | Finely chopped fresh fish | Wan Yaakob & Ali (1992) |
| After 21 days | Pellets (twice a day by sprinkling around the pond or tank edges) | Hidayat & Amelia (2020) |

**Cannibalism Management and Fry Survival**

Murrel are predators from childhood. So, some fish grow faster and swallow the smaller one. This is the biggest cause of loss in the nursery. In Malaysia, the young fish stayed in a group until about 35 days, they began to break up due to cannibalism (Wan Yaakob & Ali, 1992). In Indonesia, a farm started with 8,129 young ones and got only 3,112 after 45 days (Hidayat & Amelia, 2020). According to ICAR-CIFA, out of every 100 fry, 2 to 5 become “shoot fry” that kill the smaller ones. So, the fry should be graded every week. With regular grading, 25 to 35 of every 100 fry can survive.

**Conclusion**

A single female murrel can produce thousands of eggs. With good broodstock, simple tanks and a little knowledge, backyard hatcheries can supply farmers with seed, reduce pressure on wild stocks and even help restock natural waters. Murrel is also useful as a “police fish” to control overbreeding in tilapia ponds. The next time it rains, remember that a clever farmer might not need to wait for the monsoon.

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# MUSHROOM VALUE ADDITION AND PROCESSING: PRESERVATION TECHNIQUES, PRODUCT DIVERSIFICATION AND ENTREPRENEURIAL OPPORTUNITIES

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**Abstract**
Mushrooms are nutritionally valuable foods containing protein, dietary fibre, vitamins, minerals and biologically active compounds. However, their high moisture content, rapid respiration and delicate tissues make them highly perishable ,limiting their storage life to just 2-3 days and resulting in post-harvest losses and reduced marketability. Value addition offers an effective approach to extending shelf life, improving utilization and increasing the economic returns from mushroom cultivation. Preservation techniques such as refrigeration, freezing, drying, canning and pickling help reduce deterioration, while mushroom powder provides a versatile ingredient for bakery products, snacks, soups and other food formulations. Products such as biscuits, brownies, chips, pickles and jam offer additional opportunities for product diversification. Appropriate packaging, hygienic processing and suitable storage conditions are essential for maintaining product quality and safety. Furthermore, mushroom processing can support rural entrepreneurship, employment generation and supplementary income, particularly for small-scale producers. This review discusses the major preservation methods, value-added mushroom products, packaging requirements, processing challenges and entrepreneurial opportunities associated with mushroom utilization. Emphasis is placed on affordable technologies, product acceptability and the need for standardized processing practices to strengthen the mushroom value chain.

**Keywords:** Edible mushrooms, value addition, food processing, mushroom powder, post-harvest losses, preservation, entrepreneurship.

## Introduction

Mushrooms are increasingly recognized as nutritious and versatile food resources because of their protein, dietary fibre, mineral and vitamin content, together with various biologically active constituents. Their characteristic flavour and texture make them suitable for fresh consumption and incorporation into a wide range of food products. Research has also highlighted their nutritional and bioactive potential, increasing interest in their use in food formulation and processing (Kumar *et al.*, 2021).Despite these advantages, fresh mushrooms are highly perishable commodities. Their high moisture content, active metabolism, rapid respiration and susceptibility to enzymatic browning and microbial deterioration contribute to changes in colour, texture, flavour and overall quality after harvest. Inadequate storage, transportation and marketing facilities can further aggravate post-harvest losses, particularly in areas where cold-chain infrastructure is limited.

Value addition involves converting fresh mushrooms into products with improved convenience, storage stability and marketability. Processing methods such as drying, powder production, pickling

and incorporation into formulated foods can help utilize surplus produce and reduce dependence on immediate fresh-market sales. Value addition also encourages product diversification and creates opportunities for small-scale enterprises. Therefore, integrating preservation, product development, packaging and marketing is important for improving the economic utilization of mushrooms.

**Post-Harvest Deterioration and Need for Processing**

Fresh mushrooms undergo physiological and biochemical changes following harvest. Continued respiration, moisture loss, enzymatic activity and microbial growth can reduce freshness and consumer acceptance. Mechanical damage during harvesting, handling and transportation may accelerate browning and spoilage. Consequently, unsold mushrooms can become unsuitable for marketing within a relatively short period, leading to economic losses for growers and traders.

Processing provides an opportunity to convert perishable produce into products that can be stored, transported and marketed more conveniently. The appropriate method depends on mushroom species, product characteristics, available equipment, processing costs and the intended market. Conventional methods are often more accessible to small-scale processors, whereas advanced preservation technologies may provide improved quality retention but require greater investment and technical expertise (Sharma *et al*., 2024).

**Major Processing and Preservation Technologies**

**Refrigeration and freezing**

Refrigeration is commonly used to slow respiration and delay deterioration in fresh mushrooms. Its effectiveness depends on maintaining suitable temperatures, hygienic handling and appropriate packaging throughout storage and distribution. However, refrigeration alone does not eliminate spoilage, and its benefits are limited when temperature control is inconsistent.

Freezing provides an alternative for longer-term preservation. Nevertheless, freezing and thawing may alter texture and cause drip loss. Therefore, freezing conditions and any required pretreatment should be selected according to the intended application, such as soups, sauces and cooked products.

**Drying and mushroom powder**

Drying is an important preservation method because reducing moisture availability helps restrict microbial growth and improves storage and transportation convenience. Sun drying and hot-air drying are comparatively accessible methods, whereas microwave, infrared, vacuum and freeze-drying technologies provide additional options for improving drying efficiency or product quality. Drying conditions influence colour, flavour, texture, nutrient retention and rehydration properties. Pre treatments may improve drying performance, although their effectiveness varies with mushroom species and processing conditions (Yang *et al*., 2024).

Dried mushrooms can be marketed directly or milled into powder. Mushroom powder is particularly versatile because it can be incorporated into biscuits, breads, cakes, brownies, noodles, soups and savoury snacks. However, the proportion of powder added must be optimized to balance nutritional characteristics with flavour, colour, texture and consumer acceptance.

**Canning and pickling**

Canning combines appropriate heat processing with hermetically sealed containers to produce shelf-stable foods when a validated process is followed. It requires suitable equipment, controlled

processing conditions and strict food-safety management. Pickling uses acidifying ingredients, salt, spices and, in some formulations, edible oil to develop distinctive flavour and improve preservation. Mushroom pickle can be prepared for household consumption or small-scale commercialization. However, safe formulations must be based on validated acidity, processing and storage conditions rather than relying solely on oil coverage or visual appearance.

**Diversification of Value-Added Mushroom Products**

Product diversification can improve mushroom utilization by developing foods suited to different consumer preferences and market segments. Several products can be prepared using fresh mushrooms or mushroom powder.

**Mushroom brownies**

Mushroom powder can be incorporated into chocolate brownies alongside conventional ingredients such as flour, cocoa, sugar, eggs, butter and chocolate. Chocolate flavour may complement the characteristic taste of mushroom powder. However, the inclusion level should be optimized through sensory evaluation because excessive powder may affect flavour, colour and texture. Standardized formulation and baking conditions are necessary to achieve consistent product quality.

**Mushroom biscuits**

Biscuits provide a convenient option for incorporating mushroom powder into a familiar food product. Mushroom powder can be blended with wheat flour, sugar, fat, raising agents and other ingredients before dough preparation, shaping and baking. The amount incorporated influences crispness, colour, flavour and overall acceptability. Product development should therefore evaluate different inclusion levels and select a formulation that balances nutritional objectives with desirable sensory characteristics.

**Mushroom pickle**

Mushroom pickle offers a savoury product alternative for utilizing fresh mushrooms. Preparation generally involves cleaning, trimming, suitable pre treatment, draining and mixing with spices and approved acidifying ingredients. The finished product should be packed in clean, food-grade containers under hygienic conditions. Acidity, formulation, processing and storage conditions must be validated to ensure safety and acceptable shelf life.

**Mushroom chips**

Mushroom chips can be developed from thinly sliced mushrooms through suitable pre treatment, drying and, where applicable, frying. Drying helps reduce moisture before further processing, while frying can produce a crisp texture. The final quality depends on slice thickness, pre treatment, drying temperature, processing time and oil uptake. Moisture-resistant packaging is important for retaining crispness during storage.

**Mushroom jam and other products**

Mushroom jam represents a less conventional product-development opportunity in which mushroom pulp is combined with sugar, pectin and suitable acidifying ingredients. Because mushrooms are not naturally equivalent to conventional high-acid fruits, the formulation, acidity, heating conditions and preservation method require particular attention. A validated process is essential before making shelf-life or food-safety claims.

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Other potential products include soup mixes, sauces, chutneys, papad, nuggets, savoury snacks and mushroom-fortified bakery products. Earlier work on oyster mushroom products and broader reviews of mushroom processing indicate opportunities for expanding product diversity (Makkar *et al*., 2017; Singhal *et al*., 2019). Nevertheless, the commercial value of any product depends on formulation consistency, sensory acceptance, nutritional quality, safety and production cost.




**Packaging, Storage, Quality Assurance and Economic Potential**

Appropriate packaging protects mushroom products from moisture, oxygen, contamination and physical damage, helping maintain their quality and shelf life. Moisture-resistant packaging is essential for dried mushrooms and powder, while modified-atmosphere packaging and edible coatings may extend the shelf life of fresh mushrooms (Sharma *et al*., 2024). Hygienic processing, proper labelling and validated shelf-life studies ensure product safety. Value addition through dried mushrooms, powder, biscuits, chips, pickles and soup mixes can reduce post-harvest losses and create income and employment opportunities for rural households, self-help groups and small-scale enterprises, particularly in Jammu and Kashmir. However, successful commercialization depends on affordable processing, consistent product quality, consumer acceptance, market demand and regulatory compliance.

**Challenges and Future Prospects**

Limited processing facilities, technical knowledge, packaging affordability and uncertain market demand remain major challenges. Future research should focus on energy-efficient preservation, standardized formulations, nutritional quality, microbial safety, sensory evaluation and shelf-life validation. Training and improved market linkages can further promote the adoption of mushroom processing technologies.

**Conclusion**

Mushroom value addition helps to reduce post-harvest losses, diversify food products, the economic potential of mushroom cultivation and enhancing shelf life. Preservation techniques such as drying, freezing, canning and pickling, along with the development of mushroom powder and fortified foods, offer promising opportunities for improving utilization and marketability. Successful commercialization requires hygienic processing, suitable packaging, standardized formulations, validated shelf life and consumer acceptance. Furthermore, adopting affordable processing technologies and strengthening marketing linkages can promote rural entrepreneurship, generate employment and improve the livelihoods of small-scale producers. Future efforts should focus on product innovation, quality assurance and sustainable processing practices to strengthen the mushroom value chain and support its long-term growth.

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# TINY CARRIERS, TARGETED CONTROL: WHAT NANOTECHNOLOGY CAN-AND CANNOT-DO FOR INSECT PEST MANAGEMENT

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**Abstract**
Insect pests continue to reduce crop yield and quality, while repeated insecticide applications can increase costs, select for resistance, and expose non-target organisms. Nanotechnology is being explored as one way to improve how insecticidal active ingredients are formulated and delivered. Polymeric nanoparticles may protect sensitive compounds and modify their release; nano emulsions may improve the dispersion of some poorly water-soluble ingredients; and certain inorganic materials, including some physically active silica products, can act directly on insects. These approaches are not equivalent, and "nano" does not automatically mean more effective, safer, or suitable for field use. This article explains the principal types of nano-enabled insect-control products, their potential modes of action, the evidence needed to demonstrate a genuine advantage, and the environmental, regulatory, and practical questions that must be answered before wider adoption.

**Keywords:** Nano pesticides; Nano-enabled formulations; Insect Pest Management; Controlled release; Botanical insecticides; Insecticidal silica; Non-target effects

## Why look beyond conventional insecticide formulations?

Insecticides remain important tools in crop protection, but their performance depends on more than the toxicity of the active ingredient. Some compounds degrade rapidly in sunlight, volatilize, wash off foliage, or disperse poorly in water. Repeated exposure can also select for insecticide-resistant populations, and spray drift or residues can affect organisms other than the target pest. These limitations have encouraged research into formulation technologies that improve stability, delivery, or persistence (Gogos *et al*., 2012; Kah and Hofmann, 2014). Nanotechnology is one such research area-not a replacement for integrated pest management (IPM). A well-designed formulation might improve delivery of an existing insecticide or botanical compound, but it cannot by itself overcome every resistance mechanism, poor application timing, or pest-management failure. Resistant-pest management still depends on monitoring, threshold-based decisions, mode-of-action rotation, cultural practices, and conservation of natural enemies.

## What is a nano-enabled insecticides?

The term covers several different technologies. In a carrier-based formulation, an insecticidal active ingredient may be encapsulated in, adsorbed to, or otherwise associated with a nanoscale material. The carrier may influence protection, dispersion, spreading, adhesion, or release, while the active ingredient usually accounts for the principal insecticidal effect. Some materials, including certain physically active silica products, can themselves contribute to insect mortality. Nano emulsions contain small liquid droplets and are often discussed alongside nano-enabled formulations, but they

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are not polymeric nanoparticles. Because measured size depends on the method and formulation conditions, report the size distribution and structure rather than inferring nanoscale identity from a product name alone (Gogos *et al*., 2012; Kah *et al*., 2013; Kah and Hofmann, 2014).

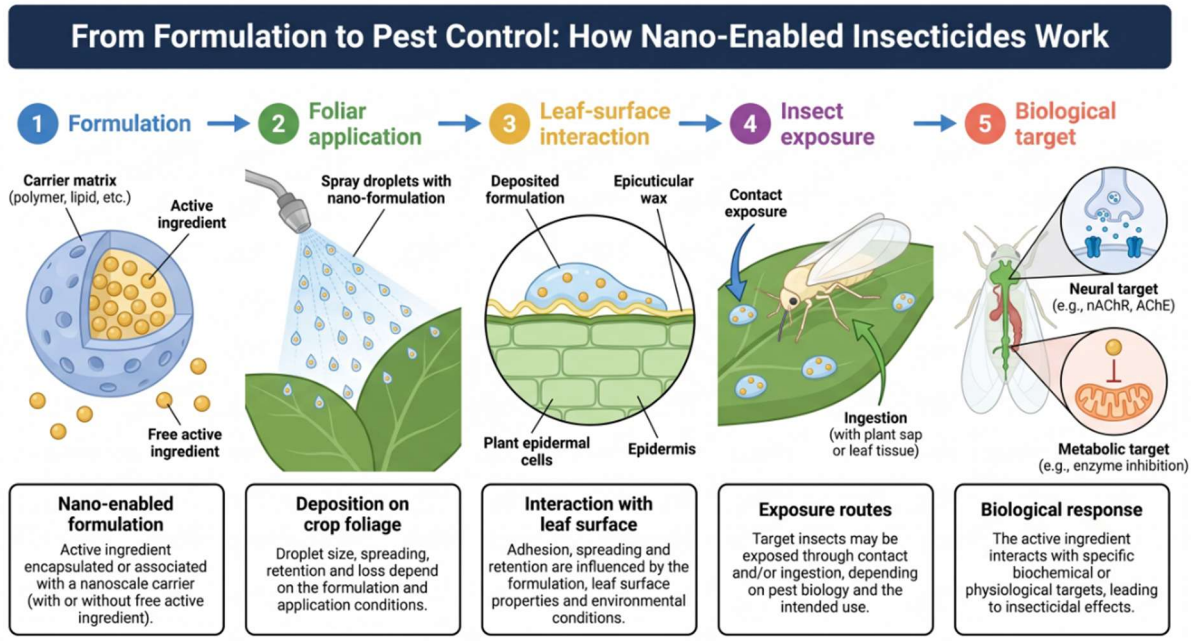



**Figure 1. Pathway of nano-enabled insecticides from formulation to pest control**

**Main types and how they may work**

**a. Polymeric nanoparticles**

Polymers such as chitosan, alginate, and poly (lactic-co-glycolic acid) (PLGA) have been investigated as carriers for compatible insecticidal compounds (Nuruzzaman *et al*., 2016). Depending on the system, active ingredients may be released by diffusion, swelling, erosion, or polymer degradation. Encapsulation may protect a sensitive compound from light or oxidation, but this outcome must be measured. A carrier can also bind an active ingredient too strongly and reduce its immediate availability. Chitosan may have biological activity of its own, so a carrier-only control is essential when testing a chitosan formulation.

**b. Nano emulsions and botanical compounds**

Neem-derived compounds and essential oils can be difficult to disperse in water or may be volatile. A suitable nano emulsion may improve dispersion and contact with treated surfaces, but these effects depend on the formulation and application conditions (Kah and Hofmann, 2014; Nuruzzaman *et al*., 2016). A smaller droplet size does not automatically mean higher insect mortality, improved penetration, or longer residual activity. Essential oils contain different chemical constituents, and their effects may involve several physiological targets; a mode of action should not be assigned to the whole category without evidence for the specific compound and pest.

**c. Insecticidal silica and other inorganic materials**

Certain physically active silica dusts, including some diatomaceous-earth products, can adsorb or remove protective lipids from the insect cuticle, increase water loss, and cause death by desiccation in susceptible insects. This mechanism should not be generalized to every silica material. Conventional diatomaceous earth is not automatically a nanomaterial; nanoscale classification

requires product-specific particle-size and structure evidence (Mucha-Pelzer *et al*., 2008; Ibrahim *et al*., 2024). Silver, zinc oxide, and copper oxide nanoparticles have shown insecticidal or other biological activity in some experimental systems, with proposed mechanisms including oxidative stress, membrane effects, and effects associated with released metal ions. Their relative contributions depend on material properties, dose, exposure route, and test organism. Laboratory toxicity alone does not establish field efficacy or an environmentally acceptable crop-protection product (Kah *et al*., 2013; Kah *et al*., 2018).

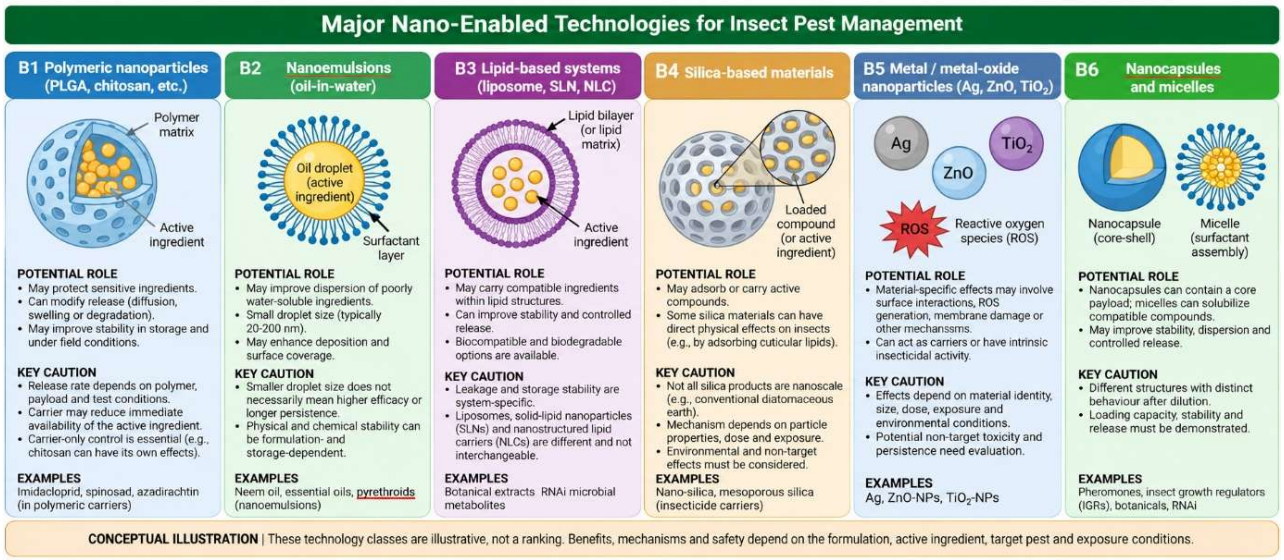



***Figure 2. Major nano-enabled technologies for insect pest management: potential roles and key limitations.***

**Table 1. Practical checks for evaluating nano-enabled insecticide claims.**

| Check | Evidence to report | What not to infer |
|---|---|---|
| Nanoscale identity | Particle or droplet size distribution, structure/morphology, measurement method, and dispersion conditions. | The word "nano" on a label does not establish nanoscale identity; hydrodynamic and microscopy-based sizes are not interchangeable. |
| Formulation function | Loading and unencapsulated fraction; release, deposition, or stability measurements when those benefits are claimed. | Encapsulation alone does not prove controlled release, protection, improved retention, or reduced degradation. |
| Efficacy advantage | Relevant controls, matched active-ingredient doses, dose-response, observation time, and independent experimental units. | Higher mortality at one time point does not prove controlled release, a lower effective dose, or longer residual activity. |
| Safety and use | Crop response, relevant non-target tests, plausible environmental exposure, worker considerations, and applicable registration/label status. | Laboratory toxicity does not establish field value, environmental safety, or legal approval for a particular use. |

**Mode of action: the carrier is not always the insecticide**

A critical distinction is between the carrier's formulation function and the active ingredient's biological target. If imidacloprid is encapsulated in a polymer, the active ingredient remains a Group 4A neonicotinoid that acts as a nicotinic acetylcholine receptor (nAChR) competitive modulator; if chlorantraniliprole is used, it remains a Group 28 ryanodine receptor modulator (IRAC, accessed 21

October 2026). These examples describe the active ingredients, not proof that nano formulations are commercially available. A delivery system may alter exposure or persistence but claims of a new biochemical mode of action require direct evidence. Similarly, a formulation that causes greater mortality at one observation time has not necessarily demonstrated controlled release. Controlled release requires release measurements over time; prolonged pest control requires separate residual-efficacy bioassays. Better initial toxicity, longer residual activity, reduced application rate, and lower non-target risk are different claims and should be tested separately.

**How should a nano-insecticide be evaluated?**

A credible study begins with a defined target pest, active ingredient, and formulation objective. Characterize the formulation before interpreting bioassays. Dynamic light scattering (DLS) can estimate hydrodynamic size and polydispersity; zeta potential can help assess dispersion behaviour; microscopy can examine morphology; and a validated chemical method should quantify total and unencapsulated active ingredient. These measurements are complementary, not interchangeable (Kah *et al*., 2013; Kah *et al*., 2018).

Bioassays should include an untreated control, a carrier-only control, any necessary solvent or surfactant control, the unformulated active ingredient, and the nano-enabled formulation. Compare the formulation and unformulated ingredient at equivalent active-ingredient doses; include a registered reference insecticide where appropriate. Choose treated-leaf residue, diet-incorporation, direct-contact, or whole-plant assays according to pest biology and the intended exposure route. Use independent experimental units, adequate replication, and a dose range that supports estimation of a concentration-response relationship. Report mortality and control mortality, observation time, insect stage, environmental conditions, and formulation batch. Estimate $LC_{50}$ or another relevant endpoint with confidence intervals where the data support it. If insects share a container or treated leaf, that container or leaf may be the true experimental unit; treating each insect as independent can cause pseudo replication. To test residual efficacy, expose fresh insects to treated material at defined intervals. Greenhouse and field trials are then needed to determine whether laboratory benefits persist under realistic conditions.

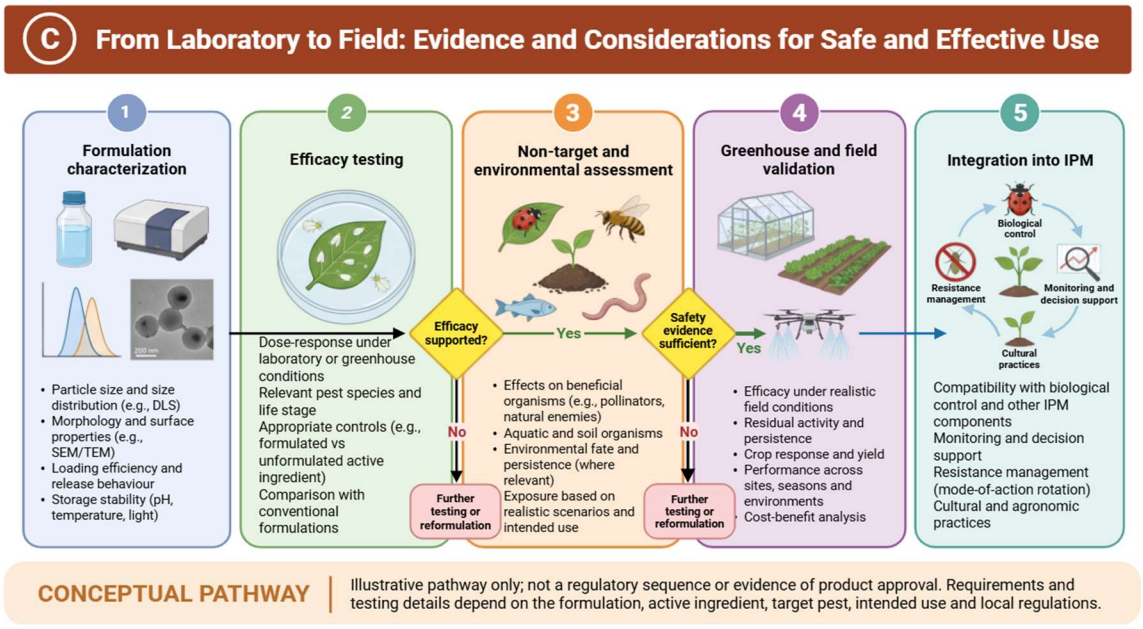



**Figure 3. Evaluation pathway for nano-enabled insecticides: efficacy, safety, field validation and IPM integration.**

**Potential benefits-and what must not be assumed**

Potential advantages include improved dispersion of poorly soluble ingredients, protection of sensitive compounds, greater retention on a target surface, or release over a longer period. Whether any of these benefits occur depends on the formulation and application conditions. A formulation can also perform worse than the unformulated active ingredient if the active compound is not released effectively or if the carrier interferes with contact. It is not scientifically defensible to assume that nano pesticides always require lower doses, prevent resistance, are harmless to beneficial insects, or degrade rapidly in the environment. Nanomaterials may interact differently with soil, water, plant surfaces, and organisms depending on composition, coating, size, aggregation, and dose. Effects on pollinators, parasitoid, predators, soil organisms, and aquatic species need assessment, alongside residues, environmental fate, and worker exposure (Kah *et al*., 2013; Kah and Hofmann, 2014; Kah *et al*., 2018).

**Commercial products: verify before naming**

Research papers often report laboratory formulations that have never become registered commercial products. Conversely, a commercial pesticide may use a formulation technology without its label describing it as “nano”. A trade name should be called a nano-insecticide only when reliable manufacturer documentation identifies the relevant nano-enabled technology and the product’s approved use can be verified. In India, consult the Central Insecticides Board and Registration Committee and the applicable product label. Internationally, verify the registration and label requirements in the country where the product is sold. Nano-fertilizers are not insecticides, and marketing language alone is not evidence of insecticidal registration.

**Conclusion: a tool to test, not a shortcut**

Nano-enabled formulations offer useful research possibilities for improving the delivery of selected insecticidal compounds, but they are not a universal solution to insect pest problems. Their value should be judged by reproducible formulation data, fair comparisons with conventional formulations, dose-response and residual-efficacy results, crop safety, effects on beneficial organisms, environmental fate, and cost. The most responsible path is to integrate promising formulations into IPM only after evidence supports their effectiveness and risk profile. In pest management, “nano” describes a technology; it is not a guarantee of better control or greater safety.

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# BIOCHEMICAL ENZYME RESPONSES AS BIOMARKERS OF POTENTIALLY TOXIC ELEMENTS TOXICITY IN AQUATIC ORGANISMS (FISH)

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**Abstract**
Potentially Toxic Elements (PTEs) have raised serious environmental concern due to their long persistence, toxic nature and bio-accumulation potential, which eventually leads towards aquatic ecosystem contamination/degradation. Increasing urbanization, industrialization as well as mining and agricultural activities increase the burden of metal (PTEs) in the natural environment system. PTEs accumulate in water-based ecosystems and are more dangerous to aquatic organisms as well as humans when their concentration reaches beyond the threshold limits. Biochemical assays are used as a sensitive biomarker for measuring stress due to PTEs induced toxicity in aquatic organisms (fish). Alteration in enzyme activities in fish is an early indicator of toxicity and environmental degradation. This review summarizes the sources of heavy metals and commonly used enzymatic biomarkers in environmental monitoring programmes.

**Keywords:** Potentially Toxic Elements, Enzyme Responses, Biomarkers, Fish

## Introduction

Potentially Toxic Elements (PTEs) are among the most hazardous pollutants in aquatic ecosystems because they are non-biodegradable, persistent and bio-accumulative in nature (Das *et al.,* 2023; Kumar *et al.,* 2024a, b). PTEs in aquatic systems can originate from different sources, such as industrial discharges and mining operations, along with leaching caused by the runoff effect or discharge of municipal and industrial wastewater and emission from fossil fuel burning, etc., (Samanta *et al.,* 2020, 2021; Kumar *et al.,* 2025a, 2026). After dispersion in aquatic compartments, PTEs that remain dissolved in water or are accumulated along the food chain and are stored by sediments represent long-term contaminant sinks (Saha *et al.,* 2024).

Fish are known indicator organisms potentially affected by PTEs. Fish absorb PTEs through the gills and food, as well as skin, and bioaccumulate in fish tissue. These pollutants can then be biomagnified along the trophic food chain, ultimately entering organisms such as human beings that may pose a carcinogenic and non-carcinogenic risk to human health (Tiwari *et al.,* 2017; Kumar *et al.,* 2024b, 2025a). Thus, the biological effects of PTEs in fish are monitored and studied as bioindicators for assessing ecosystem health. Figure 1 explains the PTEs sources, pollution, bioaccumulation, toxicity, effects and health assessment.

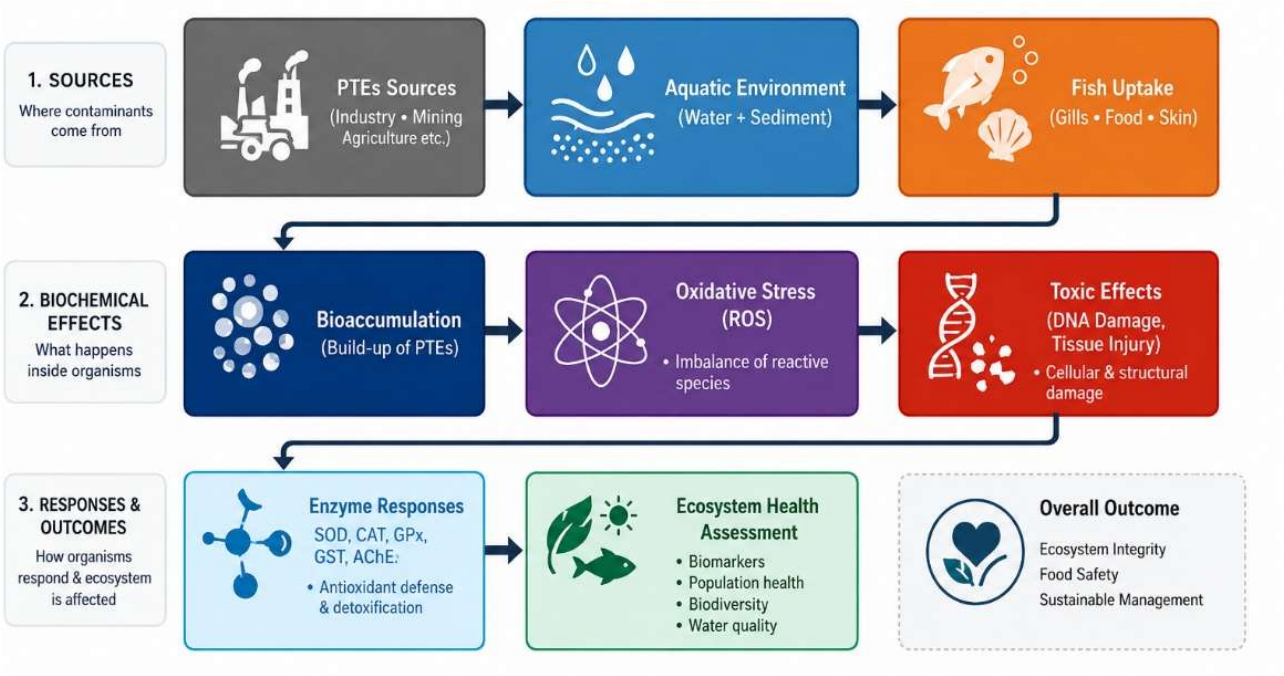



***Figure 1. PTEs sources, pollution, bioaccumulation, toxicity, effects and health assessment.***

**Bioaccumulation of PTEs and their Toxicity**

PTEs cannot be easily metabolically transformed or excreted; they can bioaccumulate in the course of time. Bioaccumulation can bioconcentrate via biomagnification through aquatic food webs into biota, in turn increasing ecological/public safety threats. Cytotoxic impact on aquatic organisms mediated by mechanisms associated with disruptions in metabolism and oxidative stress. It induces toxicity primarily by altering redox homeostasis and producing reactive oxygen species (ROS) which ultimately cause damage to lipids, proteins and DNA. Acute and chronic exposure leads to growth inhibition, reproductive dysfunction, tissue damage and disruption of physiological processes (Bhat *et al.,* 2025).

**Enzyme Assays as Biomarkers**

Environmental stressors like PTEs can directly affect enzyme activities; this makes an increase in the use of enzyme assays for ecotoxicological studies. It was reported that PTEs/stressors can bind the active site of enzymes or induce oxidative damage, thus leading to inhibition and/or activation of enzyme activities due to actions (metabolic/physiological) on cellular processes required for normal cell functions affiliated with regulation. For this reason, enzyme biomarkers give vital physiological information concerning the exposed organism to a contaminant (Kumar *et al.,* 2022a, b; Das *et al.,* 2024). Figure 2 describe the ROS generation, biochemical enzyme responses as biomarkers of PTEs toxicity and cellular protection.

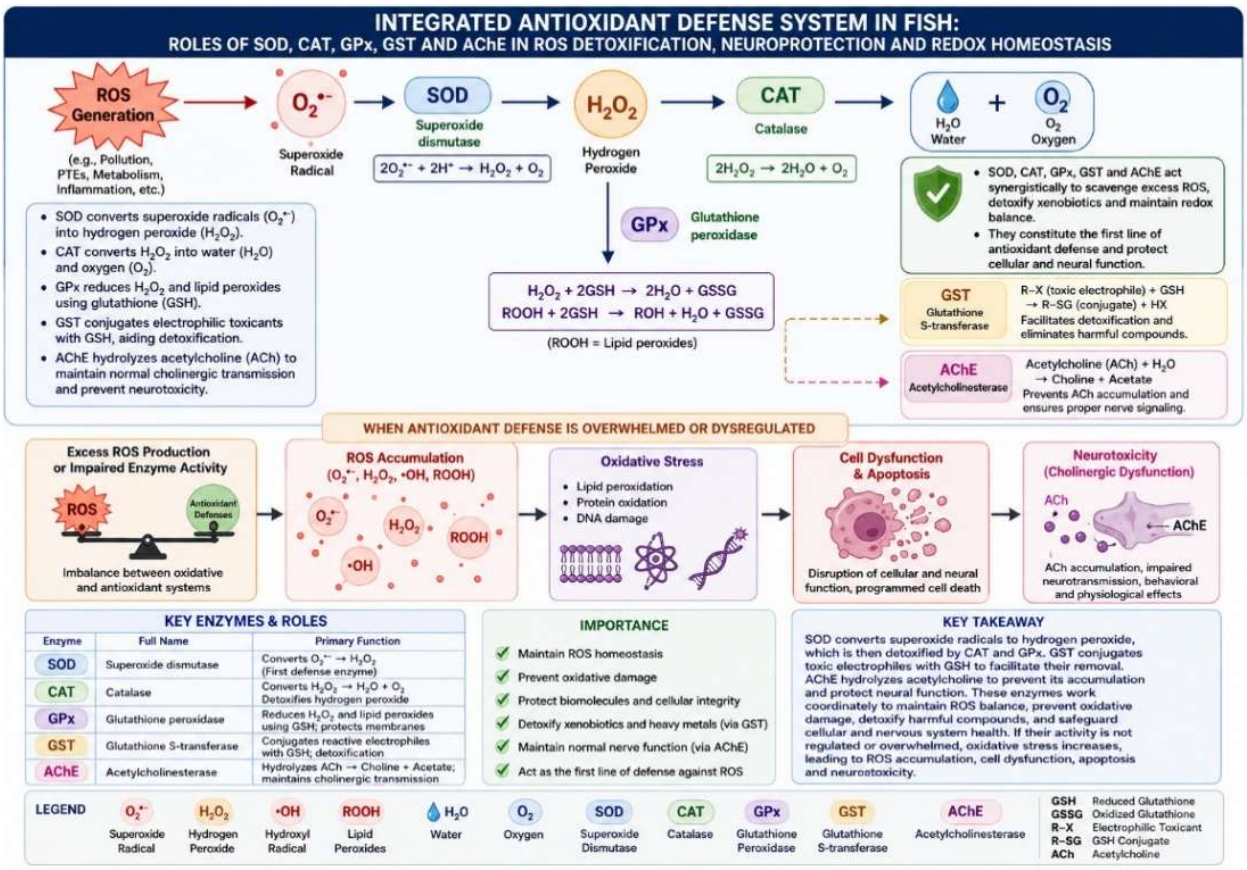



***Figure 2. Schematic representation of ROS generation, biochemical enzyme responses as biomarkers of PTEs toxicity and cellular protection.***

**Antioxidant, Detoxification, and Neurological Enzymes**

Antioxidant enzymes are one of the most used biomarkers for PTEs toxicity. Superoxide dismutase (SOD) catalyzes the reaction of superoxide radicals ($O_2^-$), forming hydrogen peroxide ($H_2O_2$); while, subsequently, catalases (CATs) convert hydrogen peroxide into water and oxygen. SOD and CAT are potent antioxidants maintaining ROS equilibrium by neutralizing the excess $O_2^-$ (i.e., superoxide) formed in tissues, as well as $H_2O_2$ within body, possibly providing a primary line of defence against various xenobiotic/ stressors (Upadhyay *et al.,* 2021). The overexpression of SOD could affect cell homeostasis coupling (Bhat *et al.,* 2025). Whenever the amount of reactive oxygen species (ROS) exceeds its removal ability, oxidative stress caused by high concentrations of ROS in cells gradually accumulates and ultimately leads to normal cell apoptosis. Glutathione peroxidase (GPx) is an enzyme involved in antioxidant defence through the reduction of hydrogen peroxide as well as lipid peroxides. Glutathione-S-transferase (GST) is a family of detoxification enzymes that play key roles in the conjugation reaction between reduced GSH and various reactive electrophilic compounds to generate more hydrophilic, less toxic metabolites for removal from organisms (Kumar *et al.,* 2022b; Bhat *et al.,* 2025). GST also plays a role in defence against oxidative damage of the tissue. Various organisms exposed to heavy metal pollution are characterized by high GST activities (Bhat *et al.,* 2025). It is also playing a role in scavenging $H_2O_2$ and lipid hydroperoxides (Kumar *et al.,* 2025b). Acetylcholinesterase (AChE) is one of the core enzymes in nerve impulse transmission (Das *et al.,* 2024). Inhibition of AChE activity by PTEs is likely to impair neurological function.

In summary, antioxidant and neurotoxicity-related enzymes can serve as highly sensitive biomarkers of PTE-induced toxicity in fish/aquatic animals. Changes in the activities of SOD, CAT, GPx and GST are indicative of disturbance in ROS homeostasis coupled with antioxidant and detoxification adaptations exhibited by an organism. The AChE activity changes can additionally suggest possible neural dysfunction following PTEs exposure. All of these enzymatic responses indicate that they have a significant role as early warning signs for oxidative and physiological stress in aquatic organisms exposed to trace elements.

**Conclusion**

Potentially toxic elements (PTEs) are persistent, bio-accumulative and harmful pollutants that can affect aquatic organisms, including fish, as well as ecosystem health. Concentration-based monitoring alone may not be a good reflection of the biological effect; thus, biochemical enzyme responses are reliable early indicators of metal-induced stress. Together, antioxidant enzymes like SOD, CAT and GPx, the detoxification enzyme GST as well as a biomarker of neurotoxicity AChE can offer significant information on oxidative stress/detoxification responses or neurological impairment in fish. In conclusion, the simultaneous PTEs concentration measurements and relevant enzymatic biomarkers can improve future studies on aquatic ecosystem health assessment along with effective environmental monitoring and management.

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# ONTOGENETIC CHANGES IN FEEDING ECOLOGY OF FISHES

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**Abstract**
A fish's dietary niche changes during every stage of its life. This shifting interaction between fish, prey, and habitat as individuals develop from larvae to adults is captured by ontogenetic dietary changes (ODS). While prey availability, behavior, competition, and predation influence real diet choice, changes in body form and feeding ability increase the range of available resources. With major implications for fisheries and ecosystem management, these changes have the potential to reorganize trophic connections, influence growth and survival, and change the ecological role of fish across life stages.

**Keywords:** Ontogenetic dietary shifts; feeding ecology; prey selection; trophic interactions

## Introduction

An ODS refers to a change in the composition, size or type of food consumed as a fish develops from larva to juvenile to adult. There is not a uniform path; some species continue to be planktivorous, herbivorous, or generalists throughout their lives, while others move from zooplankton to benthic invertebrates and ultimately fish prey. Because food availability, competition, predation risk, and habitat use interact at the individual, population, community, and ecosystem levels, ODS is better understood as an ecological phenomenon rather than a set developmental rule (Sánchez-Hernández *et al.*, 2019).

The initial limits are determined by morphology. Fish larvae are limited to small, sluggish prey due to their small mouth gape and limited swimming abilities after they hatch. Gape width, jaw structure, and swimming ability all increase with body size, increasing the variety of prey that can be caught. Around 9 mm in length, chironomids and micro-crustaceans dominated the diet of larvae in age-0 smallmouth bass (*Micropterus dolomieu*) by 15 mm, larger aquatic insects were largely consumed as the mouth size and fin development advanced (Easton & Orth, 1992). The larvae of rohu (*Labeo rohita*) and singhi (*Heteropneustes fossilis*) showed a similarly tight connection between mouth size and prey size, when offered zooplankton ranging from 75 to 2200 µm, both species gradually selected larger prey as they grew, maintaining almost constant prey-size-to-mouth-size ratio during the first four weeks after hatching. Additionally, the dietary composition changed from rotifers to cladocerans during the first two weeks, and a mixed diet produced far better growth than an exclusive copepod diet (Mookerji & Rao, 1994). However, a fish's ability to eat is determined by its behavior, not by its morphology. Coughlin (1991) demonstrated that feeding skills significantly increased during the first two weeks of exogenous feeding using video recording of first-feeding

Atlantic salmon (*Salmo salar*). After around seven to ten days, larvae switched from using a body-ram strategy swimming to overtake prey to suction feeding, which involves expanding the orobranchial chamber to suck prey into the mouth.

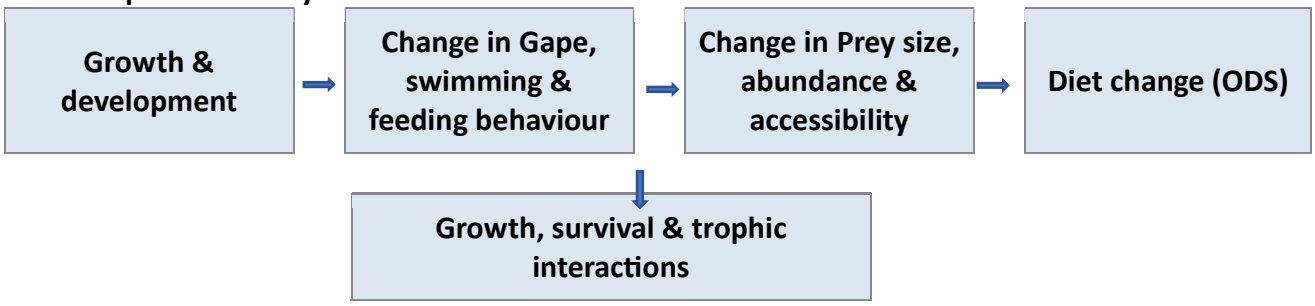
A wider gape does not guarantee a change in diet, because the prey must also be there, available and accessible. Griffiths (1975) suggested that predators either select prey based on energetic profitability or consume prey according to their availability. Therefore, both prey availability and active prey selection determine a fish's actual diet, and seasonal or habitat-driven variations in prey quantity can alter the timing and direction of an ontogenetic transition.

**Changes in Diet and Prey Composition**

A shift toward piscivory is one of the most noticeable signs of ODS. Daly *et al.*, (2009) observed this transition in young and subadult Chinook salmon (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*). Fish prey made up approximately 55% of the diet by weight for Chinook salmon in the smallest size class (80–100 mm), but this percentage increased to almost 95% for fish larger than 375 mm. A similar transition happened in coho salmon at about 240 mm fork length, when the diet began to consist primarily of juvenile forage fish. Notably, this dietary shift was not consistently associated with subsequent adult survival across salmon populations and years, suggesting that a dietary shift does not necessarily indicate improved fitness.

ODS is not limited to young or smaller fish. McElroy *et al.*, (2006) studied 565 stomachs from sandbar sharks (*Carcharhinus plumbeus*, 59–190 cm total length) and found that while cephalopods and elasmobranchs became more significant as shark size increased, prey diversity also increased with body size. In contrast, crustaceans made up a larger portion of the diets of smaller sharks. This shows that ontogenetic dietary change can continue throughout the development of large marine predators, well beyond the larval and juvenile stages.

**A Conceptual Pathway**




**Ecological and Fisheries Implications**

By allowing various size classes to take advantage of distinct food resources, ontogenetic dietary changes (ODS) can affect intraspecific competition. Coexistence between individuals and species with overlapping habitats may be made easier by such resource partitioning. Because fish may hold different trophic levels at different phases of their lives, ODS can potentially affect the structure of the food web. A juvenile fish that mostly eats zooplankton, for instance, would occupy a lower trophic position, whereas larger individuals might eat fish or invertebrates and serve as higher-level predators. These dietary changes are also important in fisheries and aquaculture. Studies based only on adult fish may overlook important differences in feeding ecology among life stages. The interpretation of stomach-content data, food-web linkages, stock assessment, and habitat management can all be enhanced by an understanding of ODS.

**Conclusion**

Fish are not ecologically the same species throughout their lives, as evidenced by ontogenetic dietary changes. Growth alters what a fish can physically consume, but whether or not that ability is demonstrated relies on a number of factors, including the availability of prey, competition, risk of predation, habitat, and feeding habits. These changes affect individual growth and survival as well as the structure of large food webs, from a larva feeding on rotifers to an adult salmon or shark eating other fish. Understanding fish populations and their ecological responsibilities during various life stages requires an understanding of size- and stage-dependent feeding habits.

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# ARTIFICIAL INTELLIGENCE AND BIOINFORMATICS: TRANSFORMING CROP IMPROVEMENT IN INDIAN AGRICULTURE

**Ravi[1,2], Ashish Gupta[1,2] and Mriyanshi Das[2]**

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## Introduction

Indian agriculture needs to increase crop productivity while adapting to climate change, emerging diseases and rising food demand. These issues can be addressed with the use of AI (Artificial Intelligence) and Bioinformatics. While bioinformatics is concerned with analysing biological data like DNA sequences, gene expression, and molecular markers, AI on the other hand is focused on finding patterns in complex data and making predictions. They can be used simultaneously to help with the discovery of genes, breeding and analysing crop traits. But the models need to be validated with the appropriate biological and field studies. The article explores how AI and bioinformatics can be used in Indian agriculture, the tools available, and some of the challenges that need to be addressed.

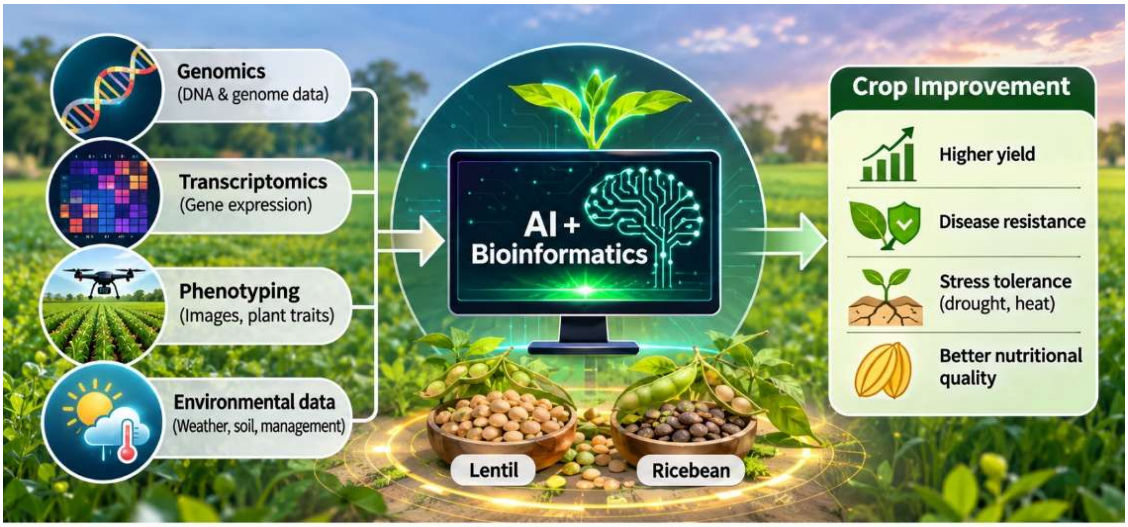



***Figure 1: Integrated use of AI and bioinformatics for crop improvement in Indian agriculture.***

## Applications in Crop Improvement

### 1. Genome Analysis and Gene Discovery

Bioinformatics tools support in the identification of genes, genetic variability analysis and functional annotation. AI methods can be employed to aid potential candidate genes by their sequence features, annotations, and gene expression patterns. These approaches can guide research on drought tolerance, disease resistance and nutritional quality, but predicted functions require biological validation (Bose *et al*., 2024).

The integration of genomic resources and transcriptomic data with field observations can be useful for various varieties of crop-improvements such as lentil and ricebean. The published ricebean genome provides a foundation for further genetic analysis and crop improvement in ricebean (Francis *et al*., 2023).

**2. Machine Learning in Molecular Breeding**

Marker-assisted selection is based on the use of markers associated with a desirable property, whereas genomic selection is based on genome-wide markers and utilizes them to predict the breeding values of candidate lines. The relationships between genetic and observed traits and the environment can be investigated using machine-learning models. The quality of data, characteristics of populations and the environment covered by training data are the factors that affect their predictive accuracy (Crossa *et al*., 2017). These predictions should complement established breeding methods and field trials.

**3. Identifying Climate-Resilient Crops**

Transcriptomics deals with the study of gene-expression in response to abiotic stress conditions like droughted and heat stressed environments. The RNA-sequencing analysis could reveal differentially expressed genes and functional annotation and pathway analysis could be helpful to interpret their potential role. These results along with variation in the genome and phenotypes, may be used to prioritize candidate genes for further study. For example, integrating gene-expression information of lentil plants in drought conditions with field observations may assist in selecting genes that could be candidate genes for drought response to be investigated further and validated. It is important to note that changes in gene expression is not sufficient proof of stress tolerance, independent evidence and appropriate validation are required (Bose *et al*., 2024).

**4. AI-Assisted Phenotyping**

Computer vision and deep-learning techniques can be used to process images taken from ground-based cameras or drones, and estimate plant characteristics like plant height, canopy cover and leaf characteristics. Integration of image-derived measurements and genomic and environmental data could improve the ability to investigate genotype and phenotype relationships and growing conditions. Models should be tested across different varieties, locations and lighting conditions before wider application (Sheikh *et al*., 2024).

**Practical Workflow and Tools**

An integrated workflow starts with reliable phenotypic observations and genomic or transcriptomic data. These datasets are then used in reproducible bioinformatics pipelines to prioritise candidate genes, predict breeding values or classify plant traits before being used to train AI models. Predictions should not be used in breeding programmes until they have been subjected to independent evaluation, biological validation and multi-location field trials.

Applications include the use of BLAST for sequence comparison, HISAT2 for alignment of RNA sequencing reads (Kim *et al*., 2019), DEseq2 for differential-expression analysis (Love *et al*., 2014), and scikit-learn for machine learning (Pedregosa *et al*., 2011). The choice of tools used should be determined by the research question and data set. It is important to be able to reproduce the results, which can be achieved by documenting the parameters, collecting appropriate training data, and conducting independent evaluation.

**Opportunities for Indian Agriculture**

AI and bioinformatics can improve the use of genomic, transcriptomic and phenotypic data in Indian crop-improvement programmes. Applications range from prioritization of genes involved in stress tolerance, genomic prediction, and scaling up plant trait analysis. In different crops, combining molecular information with standardised field observations could help identify candidates for further testing.

**Challenges and Future Prospects**

There are significant challenges such as inconsistency in data formats, limited integration of molecular and field-trial data, unequal access to computing and phenotyping resources, and lack of interdisciplinary expertise. Models created in one area or population may not be equally effective in other areas or populations. Standardised metadata, reproducible workflows, transparent reporting and collaboration between different bioinformaticians, breeders, geneticists and agronomists are therefore needed. AI should support, rather than replace, experimental validation and conventional breeding.

**Conclusion**

Gene discovery, genomic selection, stress-response analysis and image-based phenotyping, among other tools, can be applied to crop improvement with the aid of AI and bioinformatics. They are useful only if they are supported by reliable data, proper analysis techniques and external verification. The molecular data will be useful in combination with field data to help make useful breeding decisions based on computational predictions.

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# PCR: A POWERFUL MOLECULAR TOOL FOR PLANT DISEASE DIAGNOSIS

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**Abstract**
Early and accurate identification of plant pathogens is essential for effective disease management. Polymerase chain reaction (PCR) is a widely used molecular technique that amplifies specific DNA sequences, enabling pathogen detection from small amounts of biological material. In plant pathology, PCR supports pathogen identification, disease diagnosis, seed health testing and disease surveillance. Advances such as real-time PCR, multiplex PCR and digital PCR have expanded its diagnostic applications, making PCR-based techniques are valuable tools in plant disease research and management.

## Introduction

Accurate identification of plant pathogens is essential for effective disease management and crop protection. Conventional diagnostic methods, including morphological examination, pathogen isolation and pathogenicity testing, remain important but may require considerable time and expertise. Molecular diagnostic techniques provide complementary approaches for detecting pathogens with greater specificity.

Developed by Kary B. Mullis in 1983, PCR enables the selective amplification of a target DNA sequence from a complex biological sample. In plant pathology, it is widely used to identify fungal and bacterial pathogens, confirm pathogen identity and support disease surveillance. RNA pathogens, including many plant viruses, can be detected using reverse transcription before PCR amplification. PCR-based diagnostics have become important tools in modern plant disease research and laboratory diagnosis (Venbrux *et al*., 2023).

## Principle of PCR

PCR relies on the repeated enzymatic amplification of a specific DNA region using sequence-specific primers and a thermostable DNA polymerase. The reaction proceeds through three major stages: denaturation, primer annealing and extension. Repeated thermal cycling produces millions of copies of the target sequence under suitable reaction conditions.

The specificity of PCR depends largely on primer design, while amplification efficiency is influenced by template quality, reaction components and cycling conditions.

## Materials Required

The principal materials and equipment required for conventional PCR include:

- **Template DNA:** Extracted from infected plant tissues, seeds or pathogen cultures.
- **Forward and reverse primers:** Define the target DNA region to be amplified.
- **Thermostable DNA polymerase:** Commonly Taq DNA polymerase.
- **Deoxynucleotide triphosphates (dNTPs):** Building blocks required for DNA synthesis.

- **PCR buffer and magnesium ions:** Maintain suitable conditions for enzyme activity.
- **Nuclease-free water:** Used to prepare the reaction mixture.
- **Thermal cycler:** Regulates the temperature cycles.
- **Micropipettes and sterile tips:** Ensure accurate liquid handling.
- **PCR tubes:** Hold the reaction mixture.

**Mechanism of PCR**

PCR amplification involves three fundamental steps.

**1. Denaturation:** Double-stranded DNA separates into single strands at approximately 94–95°C.

**2. Annealing:** The temperature is lowered, commonly to 50–65°C, allowing primers to bind to complementary sequences flanking the target region. The optimum temperature depends on the primer melting temperature (Tm) and assay design.

**3. Extension:** DNA polymerase synthesizes new DNA strands, commonly at approximately 72°C when Taq DNA polymerase is used.

These steps are repeated for approximately 25–35 cycles. Under ideal conditions, the amount of target DNA approximately doubles per cycle, resulting in exponential amplification. The amplified DNA can subsequently be analysed to determine whether the expected target sequence is present.

**Table 1. Typical thermal cycling conditions for conventional PCR**

| Cycle step | Temperature | Duration | Number of cycles |
|---|---|---|---|
| Initial denaturation | 94–95°C | 1–3 min | 1 |
| Denaturation | 94–95°C | 10–30 s | 25–35 cycles |
| Annealing | 5°C below primer Tm | 20–30 s | 25–35 cycles |
| Extension | Approximately 72°C for Taq DNA polymerase | 30–60 s, depending on amplicon length | 25–35 cycles |
| Final extension | Approximately 72°C for Taq DNA polymerase | 5–10 min | 1 |
| Final hold | 4°C | Until sample collection | Continuous |

*Note: These are typical illustrative conditions, not universal settings. Actual temperatures and durations depend on primer characteristics, target length, polymerase and the validated protocol (Lorenz, 2012).*

A conventional PCR run often takes approximately 1–2 hours, although the duration varies with the instrument and cycling programme. Agarose gel electrophoresis requires additional time for product detection.

**Different Types of PCR and Their Applications in Plant Pathology**

PCR technology has evolved into several formats to meet different diagnostic requirements.

1. **Conventional PCR (cPCR):** Amplifies a specific DNA sequence, with products generally visualized using agarose gel electrophoresis. It is commonly used for pathogen identification and molecular characterization.
2. **Reverse-transcription PCR (RT-PCR):** Converts RNA into complementary DNA (cDNA) before amplification. It is particularly useful for detecting RNA plant viruses and other RNA targets.

3. **Quantitative real-time PCR (qPCR):** Monitors DNA amplification through fluorescence during each cycle. With appropriate standards or validated methods, it enables quantification of pathogen DNA.
4. **Reverse-transcription quantitative PCR (RT-qPCR):** Combines reverse transcription with real-time quantitative PCR. It is widely used to detect and quantify RNA viruses and investigate gene expression.
5. **Multiplex PCR:** Uses multiple primer pairs in a single reaction to detect two or more target sequences simultaneously. It supports differential diagnosis when similar symptoms may be caused by different pathogens.
6. **Nested PCR:** Uses two successive rounds of amplification with outer and inner primer sets. It can improve sensitivity and specificity for low-abundance targets, although additional handling increases the risk of contamination.
7. **Digital PCR (dPCR):** Divides a sample into numerous individual reaction partitions and estimates target concentration from positive and negative partitions. It enables absolute quantification without a conventional standard curve.

These techniques differ in their detection methods, sensitivity, quantification capability, cost and suitability for particular diagnostic purposes (Venbrux *et al*., 2023; Chen *et al*., 2024).

**Advantages and Disadvantages**

**Advantages**

- **High sensitivity:** Detects small quantities of target nucleic acid when the assay is appropriately optimized.
- **High specificity:** Well-designed primers enable targeted pathogen detection.
- **Rapid diagnosis:** Results can often be obtained within hours after sample preparation.
- **Early detection:** Can detect target sequences before clear symptoms appear, provided the target is present above the assay's detection limit.
- **Broad applicability:** Supports the detection of fungal, bacterial and viral pathogens using suitable DNA- or RNA-based protocols.
- **Quantitative analysis:** qPCR and dPCR enable estimation of pathogen nucleic-acid abundance.
- **Simultaneous detection:** Multiplex PCR can identify several targets in a single reaction.

**Disadvantages**

- **Contamination risk:** Carry-over of amplified DNA may produce false-positive results.
- **Specialized equipment:** Thermal cyclers and associated laboratory instruments require investment and maintenance.
- **Primer dependence:** Poorly designed primers may cause nonspecific amplification or false-negative results.
- **Sample inhibitors:** Plant compounds and other contaminants may interfere with amplification.
- **Viability limitation:** Conventional PCR detects DNA but does not necessarily establish whether a pathogen is alive or actively causing disease.
- **Technical expertise:** Reliable results require appropriate sample preparation, assay validation and interpretation.
- **Cost considerations:** Reagents, equipment and probe-based assays can be expensive, particularly for high-throughput testing.

**Conclusion**

PCR has transformed plant pathology by enabling rapid and specific detection of plant pathogens at the molecular level. Its different formats offer complementary advantages, ranging from routine pathogen identification using conventional PCR to quantitative detection using qPCR and dPCR. Nevertheless, reliable diagnosis depends on validated assays, suitable controls, good laboratory practices and careful interpretation. Continued advances in molecular diagnostics are strengthening plant disease surveillance and supporting timely, evidence-based crop protection strategies.

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# NATURAL VS ARTIFICIAL BREEDING METHODS IN ORNAMENTAL FISHES

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## Introduction

Ornamental fish breeding is an important component of the ornamental aquaculture industry. The increasing demand for attractive, healthy and high-quality ornamental fishes in domestic and international markets has created a need for efficient and sustainable breeding techniques. Ornamental fishes reproduce through different mechanisms, depending on their species, reproductive biology and environmental requirements. Breeding methods are broadly classified into natural breeding and artificial breeding. Natural breeding relies primarily on the reproductive behaviour and physiological processes of the fish under suitable environmental conditions, whereas artificial breeding involves human intervention to control or facilitate spawning, fertilization and, in some species, egg incubation. Both methods play important roles in commercial seed production, conservation of native ornamental fishes, maintenance of desirable strains and development of sustainable ornamental aquaculture. Natural breeding involves providing suitable environmental conditions such as temperature, photoperiod, and substrate to stimulate spawning. Livebearers such as guppies and mollies breed naturally with minimal intervention. Induced breeding techniques involve the use of hormonal treatments to synchronize spawning, particularly in egg-laying species such as angelfish and goldfish.

## Natural Breeding Methods

Natural breeding occurs when male and female fish are placed together in a suitable environment and allowed to spawn with minimal or no direct human intervention. Breeders mimic natural habitats by adjusting water parameters (temperature, pH, and lighting), providing spawning substrates (such as plants, spawning mops, or gravel), and feeding a high-nutrition diet. Livebearers (such as Guppies, Mollies, Platies, and Swordtails) that fertilize internally and drop developed fry, as well as easy egg-layers (such as Goldfish, Zebra Danio, and certain Tetras).

## Types of natural breeding

### Pair breeding

A compatible male and female are maintained together to encourage courtship, spawning, and fertilization.

- Examples: Angelfish (*Pterophyllum scalare*) and discus (*Symphysodon* spp.).
- Suitable for species that form pairs and exhibit parental care.

### Group or harem breeding

One or more males are maintained with several females, depending on the species' reproductive behaviour.

- Examples: Guppy (*Poecilia reticulata*), molly (*Poecilia sphenops*) and platy (*Xiphophorus maculatus).*
- Commonly used for live-bearing ornamental fishes.

**Substrate spawning**

Fishes deposit eggs on a selected surface, such as aquatic plants, stones, spawning mops or artificial spawning substrates.

- Examples: Angelfish, goldfish (Carassius auratus) and zebra danio (Danio rerio).
- Spawning substrates facilitate egg collection and management.

**Bubble-nest breeding**

The male constructs a bubble nest at the water surface and usually guards the eggs after spawning.

- Examples: Siamese fighting fish (Betta splendens) and certain gouramis.
- Floating plants and calm water may support nest construction.

**Natural breeding with parental care**

One or both parents protect, fan, or otherwise care for the eggs and young.

- Examples: Discus, angelfish and several mouthbrooding ornamental cichlids.
- Parental care can improve survival when the breeding environment is properly managed.

**Advantages:**

- Low cost and simple setup requiring minimal specialized equipment.
- Less stress on the parent fish (brood-stock).
- Ideal for small-scale or hobbyist fish keepers.

**Disadvantages:**

- Low control over which specific fish pair up (unless separated in dedicated breeding tanks).
- Lower fertilization and hatching rates compared to controlled methods.
- Higher risk of parental cannibalism or fungal/bacterial attacks on eggs if not monitored

**Artificial & Induced Breeding Methods**

Artificial breeding (often involving hormone-induced ovulation or hand-stripping) is a high-control process used to manage difficult or commercial species. Induced Spawning: Hormonal treatments (such as Ovatide, Ovaprim, WOVA-FH, HCG or pituitary extracts) are administered to mature fish to synchronize and trigger spawning. Artificial Propagation/Stripping: Ripe eggs are gently massaged out of the female and mixed directly with milt (sperm) stripped from the male in a dry bowl, then transferred to controlled hatchery incubators. Egg-laying commercial and delicate species where natural spawning in captivity fails (such as certain high-value cichlids, marine ornamentals, or specialized carp/goldfish lines).

**Environmental manipulation**

Breeding conditions are modified to stimulate spawning. Techniques include controlling temperature, photoperiod, water flow, water exchange and spawning substrate.

Examples include managed spawning of zebra danios and other egg-laying ornamental fishes.

**Hormone-induced breeding**

Selected brood-stock receive an appropriate reproductive hormone treatment under professional supervision to stimulate final maturation, ovulation or spermiation.

Commonly used agents in fish hatchery practice include:

- Human chorionic gonadotropin (hCG).

- Gonadotropin-releasing hormone analogues (GnRHa), sometimes combined with dopamine antagonists.
- Other species-appropriate hormonal preparations.

The choice of treatment and dosage depends on species, maturity, broodstock condition and established protocols. Hormonal induction is not necessary for every ornamental fish species.

**Stripping and artificial fertilization**

Mature eggs and milt are collected manually from broodstock and mixed using a suitable fertilization method.

The process generally involves:

1. Selecting healthy, sexually mature broodstock.
2. Ensuring appropriate reproductive readiness.
3. Collecting eggs and milt using a species-appropriate technique.
4. Mixing the gametes to achieve fertilization.
5. Incubating fertilized eggs under suitable conditions.
6. Rearing newly hatched larvae with appropriate live feeds and water quality management.

This method is suitable for selected egg-laying species in which gametes can be collected safely and reliably. It is not appropriate for all ornamental fishes.

**Controlled egg incubation**

After spawning or artificial fertilization, eggs are maintained in hatchery incubators, trays, jars or tanks with suitable water flow and oxygenation.

The main objectives are to:

- Maintain suitable temperature and dissolved oxygen.
- Remove or manage dead and fungused eggs.
- Prevent excessive sediment accumulation.
- Monitor embryonic development and hatching.
- Improve hatchery hygiene and egg survival.

**Advantages:**

- Much higher fertilization and hatching success rates (often exceeding 90% in managed setups).
- Year-round seed availability and precise control over genetic lines and hybrid creation.
- Eliminates parental cannibalism and protects eggs from early-stage infections

**Disadvantages:**

- High capital cost for hatchery infrastructure, specialized tanks, and water-filtering systems.
- Requires technical expertise, skilled labor, and careful handling to avoid injuring brood-stock.
- Risk of stress or mortality to parent fish from hormone injections and manual stripping.

**Conclusion**

Natural and artificial breeding are complementary approaches in ornamental aquaculture. Natural breeding is often suitable for easily reproducing ornamental fishes and small-scale production systems because it requires relatively little specialized equipment and supports normal reproductive behaviour. Artificial breeding provides additional control over reproduction and can be valuable for selected species, planned hatchery production and scientific research. The choice of breeding

method should be based on species-specific reproductive biology, production objectives, infrastructure, technical expertise, cost and animal welfare. An integrated approach combining appropriate brood-stock nutrition, sound water quality management, genetic diversity and effective larval rearing can improve the sustainability and profitability of ornamental fish production.

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# FROM RISK TO RESILIENCE: THE POWER OF AGRO ADVISORY SERVICES IN MODERN FARMING

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## Introduction

Indian agriculture is often described as a "gamble of the monsoon," as irregular rainfall, droughts, floods and rising temperatures continue to threaten crop production. Between 2015 and 2021, excess rainfall and drought affected millions of hectares of cropland in India, while climate change could reduce wheat and rice yields by 10–20 per cent in many regions without timely adaptation.

Weather-based agro-advisory services help farmers turn uncertainty into informed action by combining location-specific forecasts with practical advice on sowing, irrigation, fertilization, pest management and harvesting. ICT tools such as SMS, mobile apps, WhatsApp and digital platforms further improve timely access to weather and agricultural information. Initiatives such as Gramin Krishi Mausam Sewa (GKMS) and District Agro-Meteorological Units (DAMUs) are strengthening this outreach. Farmers using such advisories have reported 10–15 per cent higher yields, 15–25 per cent lower weather-related losses and 15–20 per cent savings in water and fertilizer use.

Thus, agro-advisory services are helping Indian farmers move from reactive risk management to proactive climate resilience, supporting more efficient, stable and sustainable farming.

## Agro-Advisory Services

Agro-Advisory Services (AAS) form a network of support systems that assist farmers by offering timely information, practical skills, and suitable technologies to tackle on-field challenges and improve their livelihoods. These services mainly provide accurate, location-specific weather and climate forecasts, along with clear guidance on how upcoming conditions may affect various crops. Farmers rely on them to adjust key decisions from agronomic practices and pest-disease control to efficient water and input management based on past, present and expected weather patterns.

## Need for Agro-Advisory Services

- Enable smarter and more confident farm decisions.
- Promote sustainable and profitable agriculture.
- Improve crop productivity, quality and efficient input use.
- Address real-time, field-level farming challenges.
- Contribute to higher productivity and national food security.
- Bridge the gap between agricultural research and field-level practice.

## Importance of Agro-Advisory Services

- Increase crop productivity and farm income while reducing cultivation costs.
- Enable timely planning and faster decision-making.
- Reduce weather-related crop losses, risks and uncertainties.

- Guide farmers on irrigation, soil moisture, fertilizers and herbicide application.
- Recommend suitable sowing dates and intercultural operations.
- Provide early warnings and management advice for pests and diseases.
- Promote protective practices such as mulching, shading and microclimate management.
- Encourage climate-smart and environmentally sustainable farming practices.
- Provide guidance on livestock health, housing and nutrition.

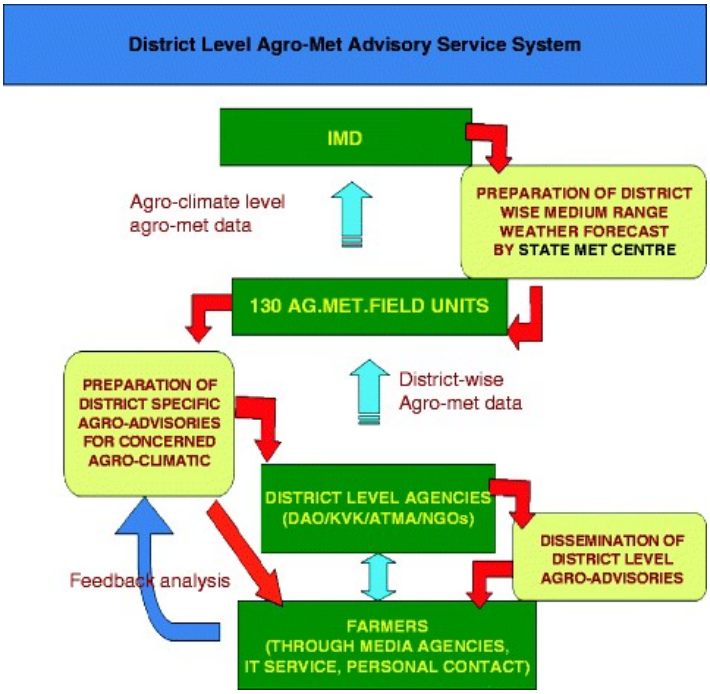



***Fig 1: Process of Preparation of Agromet Bulletin***

**Role of various stakeholders in agro advisory services:**

**Indian Council of Agricultural Research (ICAR)**

ICAR provides Kharif and Rabi agro-advisories covering crops, livestock, poultry and fisheries, with guidance on seed selection, soil and water management, nutrients, pest and disease control, and harvesting. Disseminated through 11 ATARI zones in regional languages, these advisories help farmers improve productivity, manage weather risks and enhance farm income.

**Agricultural Technology Information Centre (ATIC)**

ATIC acts as a single-window system linking research institutions with farmers and stakeholders. It provides improved seeds, planting materials, technologies and publications, while offering advisory services, consultancy, farmer feedback and agri-business support. Through training programmes, including NABARD-supported initiatives, ATIC also promotes rural entrepreneurship and employment generation.

**Kisan Call Centre (KCC)**

Launched in 2004, Kisan Call Centres provide farmers with instant expert advice in 22 languages through the toll-free numbers 1800-180-1551 / 1551, from 6:00 am to 10:00 pm. Trained Farm Tele Advisors handle queries, while complex issues are referred to specialists from ICAR, State Agricultural Universities and state departments.

**India Meteorological Department (IMD)**

Established in 1875, IMD is India's national meteorological agency, providing weather observations, forecasts and early warnings. Its services support agriculture and other sectors while alerts on cyclones, heavy rainfall, droughts, heat and cold waves help protect crops, livelihoods and property.

**History of Agro Advisory Services**

- **1932 –** Agromet Division established at IMD Pune
- **1945 –** Farmers Weather Bulletin
- **1976 –** Agromet Advisory Services (AAS) at State Level
- **1991 –** AAS at Agro-Climatic Zone Level (130 Zones)
- **2008 –** AAS at District Level (636 Districts)
- **2010 –** Micro-Level Weather based Advisory Services
- **2015 –** Gramin Krishi Mausam Sewa was started by the Ministry of Earth Sciences to provide crop-specific advice to farmers twice a week at district level
- **2018 –** Experimental AAS at Block Level (200 Blocks in 24 States) and plans to extend to ~ 6500 blocks.

**Gramin Krishi Mausam Sewa (GKMS)**

GKMS, implemented by IMD with ICAR and State Agricultural Universities, provides location-specific weather forecasts and crop- and livestock-based advisories. Issued every Tuesday and Friday, it offers five-day forecasts of rainfall, temperature, humidity, wind and cloudiness, converted into practical advice on sowing, irrigation, fertilizers, pest management and livestock care.

Key components: Weather observation and forecasting, agromet product generation, advisory preparation and dissemination, awareness, feedback, economic assessment and training.

Agromet Bulletin: Includes past weather, 5-day quantitative forecasts, crop-stage-specific and livestock advisories, and the following week's outlook. SMS advisories are limited to 262 characters.

Outreach: Uses awareness programmes, roving seminars, Kisan Melas, field demonstrations and the Meghdoot app, which provides personalized advisories in local languages.

**ICT Approaches – Digital Tools for Farmers**

**Modern digital platforms have made agro-advisories more accessible than ever:**

**Portals:**

Farmers' Portal, mKisan Portal, KVK Portal, e-Krishi, TNAU Agritech Portal and Agropedia provide one-stop information on crops, inputs, schemes, market prices, and expert advice.

**Mobile Apps have become game-changers:**

- **Kisan Suvidha:** Quick access to weather, market rates, and advisories in multiple languages.
- **IFFCO Kisan:** Offers weather updates, mandi prices, expert chat, and input purchase options.
- **Meghdoot:** Provides district- and crop-specific weather-based advisories twice a week, along with historical data and livestock guidance.
- **Damini:** Sends lightning alerts with safety tips three hours in advance.
- **Mausam:** Delivers enhanced weather forecasts, radar images, and warnings.
- Other useful apps include mKRISHI AQUA (for aquaculture), FARMS (farm machinery hiring), and Havaamaana-Krishi (local weather and advisories).

**Social Media for Agro-Advisory Services**

Social media enables rapid, interactive sharing of weather updates, pest alerts, expert advice and success stories. It strengthens two-way communication among farmers, scientists and extension workers, helping convert timely information into practical farm decisions. These digital tools support risk reduction, efficient resource use and more resilient and profitable farming under climate uncertainty.

**Conclusion**

Agro-advisory services are transforming Indian agriculture by turning weather uncertainty into manageable risk. Timely forecasts, expert guidance from ICAR and IMD's GKMS, and digital tools such as Meghdoot help farmers make informed decisions on sowing, irrigation and pest management, reducing losses and improving productivity and incomes. By connecting science with field-level action, these services are shifting farming from the "gamble of the monsoon" towards a more resilient and sustainable enterprise. Strengthening agro-advisory services is therefore vital for climate-resilient farming, secure livelihoods and national food security.

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# PEE-S OF MIND: MODERN PREVENTION AND NON-SURGICAL SOLUTIONS FOR PET URINARY STONES

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For decades, discovering that a beloved cat or dog had bladder or kidney stones (known medically as uroliths) meant facing a major open surgical procedure called a cystotomy. Today, veterinary medicine is undergoing a compassionate revolution. Clinicians are moving away from invasive open surgeries and embracing gentler, modern strategies such as medical dissolution and minimally invasive options. Why does this shift matter so much for pet parents? Avoiding open bladder surgery significantly shortens hospital stays, reduces pain, and eliminates the need for suture materials inside the bladder. Suture material left behind can accidentally act as a seed—or nidus—around which new stones form, driving up to 9% of all stone recurrences. By using modern dietary protocols and advanced endoscopy, we can remove stones while protecting our pets' comfort and long-term urinary health. Understanding these gentler alternatives empowers pet owners to make informed choices, starting with knowing when a urinary issue becomes an immediate emergency.

**Red Alert: Recognizing and Managing Urinary Obstructions**

While many urinary stones can be managed gradually, a stone that lodges in the narrow tubes of the urinary tract creates a life-threatening emergency. Blockages can occur in the ureters (the delicate tubes carrying urine from the kidneys to the bladder) or the urethra (the passage from the bladder to the outside). When urine flow is completely or partially blocked, pressure builds rapidly, causing swift, devastating damage to the Glomerular Filtration Rate (GFR)—a measure of the kidney's filtering capacity.

Research tracking the decline of GFR during ureteral blockages reveals a stark timeline of permanent loss:

1. **7 Days of Obstruction:** Results in a 35% permanent loss of kidney function.
2. **14 Days of Obstruction:** Results in a 54% permanent loss of kidney function.
3. **40 Days of Obstruction:** Results in a 100% permanent loss of kidney function.

In cats facing ureteral blockages, traditional medical management—such as intravenous fluid therapy and medication alone—is rarely effective, succeeding in only 8% to 13% of cases. Because of this high failure rate and the rapid loss of kidney function, species-specific interventional procedures have become the modern standard of care:

- **For Cats:** The preferred standards of care are Subcutaneous Ureteral Bypass (SUB) systems (externalized bypass devices that route urine around the blockage) or Ureteral Stenting (tiny internal mesh tubes that hold the ureter open).

- **For Dogs:** The primary standard of care is Ureteral Stenting, which opens the passage and can be combined with advanced stone-fragmentation techniques if needed.

Furthermore, underlying infections are extremely common during these crises; roughly 59% of dogs with ureteral obstructions have a concurrent urinary tract infection (UTI), making mandatory bacterial urine cultures a crucial part of emergency evaluation.

Once acute blockages are ruled out or stabilized, veterinarians can focus on evaluating non-emergency stones using gentle, modern techniques.

**Modern Medical & Minimally Invasive Procedures: A Quick-Reference Guide**

When non-emergency stone removal is necessary, pet owners now have access to a variety of cutting-edge, low-impact procedures. The following table provides a quick reference to these modern techniques:

| Procedure Name | How It Works | Best Used For / Primary Benefit |
|---|---|---|
| Medical Dissolution | Administering specialized, prescription therapeutic diets and targeted medications that alter urine chemistry to dissolve stones in place over time. | Best for sterile or infection-induced struvite, urate, and cystine stones located where they are bathed in urine and not causing an obstruction.Note: Calcium Oxalate (CaOx) stones cannot be medically dissolved. (CaOx accounts for >90% of upper urinary tract stones in cats). |
| Laser Lithotripsy & Basket Retrieval | Passing a tiny scope into the urethra or bladder, fragmenting stones using focused laser energy, and extracting the pieces with tiny wire baskets. | 100% effective for removing urethral stones (urethroliths) in dogs, offering a rapid recovery and an average procedure time of just ~36 minutes. |
| Percutaneous Cystolithotomy (PCCL) | A minimally invasive technique utilizing a tiny skin incision and keyhole access scope to directly view and extract stones from the bladder. | Ideal for stones too large for urethral basket retrieval, or for male cats and small male dogs whose narrow urethras cannot fit standard scopes. |
| Ureteral Stenting & SUB Systems | Implanting internal mesh tubes (stents) or artificial bypass channels (SUBs) to route urine around ureteral obstructions. | The standard of care for upper tract blockages, offering the lowest morbidity and mortality rates compared to traditional ureteral surgery. |

**A Note on "Watchful Waiting" for Asymptomatic Stones**

Not every discovered stone requires immediate intervention. If a pet has "non-clinical" or asymptomatic bladder stones that are too large to slip into the urethra or unlikely to cause a sudden blockage, immediate removal is often unnecessary. In these cases, veterinarians recommend "watchful waiting"—a strategy of periodic diagnostic monitoring (such as routine ultrasound or X-rays) paired with client education to watch for sudden symptoms, avoiding unnecessary procedures for stones that aren't causing harm.

Transitioning from procedure selection to long-term care requires a closer look at the stone's specific mineral makeup.

**Deep Dive: The Four Main Stone Types and How to Prevent Them**

Every urinary stone is unique, formed from specific mineral crystals precipitating in the urine. Managing and preventing them requires a tailored strategy based on the stone's chemical profile.

**Struvite Stones (Magnesium Ammonium Phosphate)**

Struvite stones behave very differently depending on whether they occur in cats or dogs:

- **Sterile Struvite (Common in Cats):** These stones form in the absence of bacteria. They can be dissolved medically within 2 to 5 weeks by feeding specialized therapeutic maintenance foods that are low in magnesium and phosphorus and formulated to acidify urine (keeping urine pH below 6.5).
- **Infection-Induced Struvite (Common in Dogs):** These stones form when urease-producing bacteria (most commonly *Staphylococcus* species) alter urine chemistry. The primary prevention strategy is not dietary; it is persistent elimination of UTIs. Because standard urine sediment checks under a microscope can miss active infections, routine aerobic bacterial urine cultures are mandatory. Therapeutic diets serve only as a secondary aid; without eliminating the bacteria, the stones will return.

**Calcium Oxalate Stones**

Unlike struvite, Calcium Oxalate stones cannot be medically dissolved (and notably represent over 90% of upper urinary tract stones in cats). Prevention is the only non-surgical defense.

- Hydration: Feed high-moisture canned foods (>75% water) to dilute urinary minerals. The goal is to achieve a target Urine Specific Gravity (USG)—a measure of how concentrated or diluted the urine is—of ≤1.020 in dogsand <1.030 in cats. Do not use high-sodium dry kibble as a long-term substitute for wet food to encourage drinking.
- pH Management: Avoid acidifying foods. Maintain urine pH above 6.6 in dogs and 6.25 in cats. If urine remains persistently acidic, veterinarians may prescribe alkalinizing salts like Potassium Citrate.
- Dietary Adjustments: Avoid foods containing excessive animal protein (>10 g/100 kcal on a dry matter basis), as high protein increases calcium excretion in urine while decreasing protective urinary citrate. For pet owners, this means carefully reviewing prescription food labels with your vet and strictly avoiding high-protein commercial meat treats, freeze-dried meat toppers, or table scraps.
- Medications: For pets with frequently recurring calcium oxalate stones, thiazide diuretics (such as hydrochlorothiazide) may be prescribed to help the kidneys reabsorb calcium back into the bloodstream. Because thiazides can contribute to urine acidification, veterinarians should first monitor urine pH to determine whether concurrent Potassium Citrate is necessary.

**Urate Stones**

Urate stones stem from metabolic pathways involving purines (compounds found in proteins). They are driven by genetic mutations—such as the *SLC2A9* gene mutation found in Dalmatians and Bulldogs—or liver blood vessel abnormalities known as portovascular shunts (common in Yorkshire Terriers and Pugs).

- Dissolution Strategy: A low-purine, alkalinizing diet paired with allopurinol (15 mg/kg every 12 hours) can dissolve urate stones. In studies of Dalmatians, this protocol achieved complete dissolution in ~40% of cases and partial dissolution in ~30%.
- Prevention Strategy: Provide high-moisture, low-purine diets (strictly avoiding purine-rich organ meats and fish), keep urine alkalinized (target pH ≥ 7.0), and use low-dose Allopurinol (5–7 mg/kg every 12 to 24 hours) if diet alone is insufficient.
- Critical Warning**:** Xanthine oxidase inhibitors like Allopurinol must NEVER be administered to dogs that are not on a purine-restricted diet. Doing so—or administering excessive Allopurinol doses (>9–38 mg/kg/day)—causes a dangerous buildup of xanthine, leading to the formation of severe xanthine stones.

**Cystine Stones**

Cystinuria is a genetic condition in which the kidney tubules fail to reabsorb the amino acid cystine, causing it to accumulate and form stones in acidic urine.

- Dissolution & Prevention: Management relies on feeding high-moisture, reduced-protein diets that restrict methionine (an amino acid found in protein that breaks down into cystine), limiting dietary sodium, and alkalinizing urine to a target pH of ~7.5 using potassium citrate.
- Medical Intervention: In severe or recurrent cases, thiol-binding drugs such as Tiopronin (2-MPG) at 15–20 mg/kg every 12 hours are added. Tiopronin binds to cystine to form a complex that is 50 times more soluble in urine. Elevating the urine pH to ~7.5 through alkalinization is essential, as alkaline urine directly potentiates the efficacy of thiol-binding drugs.
- Role of Neutering: Neutering intact male dogs is strongly recommended. Certain forms of cystinuria are androgen-dependent (driven by male sex hormones), and neutering also prevents passing this genetic mutation on to future generations.

With a clear picture of these mineral profiles, pet parents can consolidate these rules into a simplified daily routine.

**The Pet Parent's Hydration & Prevention Playbook**

Translating clinical recommendations into daily home care doesn't have to be overwhelming. Follow these core rules to minimize stone recurrence:

1. Prioritize Moisture First: Dilution is the solution to pollution. Always choose canned/high-moisture foods (>75% water) or add clean water directly to dry kibble to reduce the concentration of stone-forming minerals in the urine.
2. Target Specific Gravity Goals: Work with your veterinarian to test your pet's urine concentration. Strive to maintain a target urine specific gravity of ≤1.020 in dogs and <1.030 in cats.
3. Culture, Don't Just Dip: If your dog forms infection-induced struvite stones, do not rely on standard urinalysis dipsticks or microscopic checks alone. Schedule routine aerobic bacterial urine cultures monthly for 2–3 months post-infection, and then periodically as clinically indicated to catch hidden UTIs before a stone can form.
4. Avoid Unnecessary Surgery: If stones are detected, ask your veterinarian about medical dissolution or minimally invasive retrieval options (such as laser lithotripsy, PCCL, or stenting) before committing to open bladder surgery.

**Conclusion: Partnering for Lifelong Urinary Health**

Removing or bypassing a urinary stone solves an immediate problem, but it does not cure the underlying physical or genetic reasons why the stone formed in the first place. True, lasting success relies on a dedicated partnership between you and your veterinary team. By combining routine diagnostic monitoring, tailored therapeutic diets, proper hydration, and modern interventional care, you can protect your pet from recurrent stones and ensure a happier, healthier, and more comfortable life.

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# SIX-LEGGED SUPERFOODS: TINY PROTEIN POWERHOUSES FOR A HUNGRY PLANET

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Picture a school canteen where a bowl of golden-fried grasshoppers sits beside the rice and lentils and nobody blinks. For millions of people, that is simply dinner. Eating insects, known as entomophagy, is woven deeply into our evolutionary past (Fontaneto *et al*., 2011). Now, with populations growing and farmland shrinking, scientists are asking whether these small creatures could help the world avoid a protein shortage?

**Eating insects: A practice with deep roots**

Insects have long featured in diets across Africa, Europe, Asia and Latin America. More than 1,900 edible species are recorded among roughly 300 ethnic groups in 113 countries (MacEvilly, 2000), and over two billion people eat them regularly, in some regions getting a notable share of their animal protein this way (Van Huis *et al*., 2013). The menu is wonderfully varied: grasshoppers, caterpillars, beetle grubs, winged termites, bees, ant brood, cicadas and aquatic insects (Bodenheimer, 1951). Beetles lead by number of species eaten, followed by butterflies and moths, then ants, bees and wasps (Jongema, 2012). Africa is a hotspot, with surveys recording between 246 and 524 edible species across 27 to 34 countries (Van Huis *et al*., 2013). The habit is also ancient: insects have existed for at least 400 million years (Gaunt & Miles, 2002).

**Why look to insects now?**

The arithmetic of hunger is sobering: over 3.7 billion people are reported to suffer from malnutrition, largely because of too little protein and energy (Olaf & Michael, 2005). Food supply must keep pace with population growth, so the search for new, locally rooted foods continues (Van Huis *et al*., 2013). In much of Africa and Latin America, food is scarcer and imports costlier, which makes indigenous resources attractive. Insects fit the bill: they are abundant, form huge biomass and offer digestible, good-quality protein (Conconi, 1974; Wang *et al*., 2004), along with fat, vitamins and minerals, especially iron and zinc (Oliveira *et al*., 1976). Many communities already roast, fry or eat them live, so the cultural groundwork exists (Tiencheu & Womeni, 2017).

**A tiny nutritional powerhouse**

**Protein and amino acids.** Across 100 species, protein made up 13% to 77% of dry matter, varying widely between insect groups (Xiaoming *et al*., 2010). Some Amazonian communities draw 8% to 70% of their dietary protein from insects (Paoletti & Dufour, 2005). Insects also supply lysine and tryptophan, which could enrich lysine-poor cereal diets (Ekpo & Onigbinde, 2005; Elemo *et al*., 2011; Finke, 2002). The chart below compares mealworm with beef.In plain terms, mealworm matches or beats beef on the branched-chain amino acids but would need partner foods to cover lysine and methionine.

**Fats.** Insect oils tend to be rich in polyunsaturated fatty acids, including the essential linoleic and alpha-linolenic acids. In Cameroon, fat made up about 54% of dry matter in the African palm weevil

and 67% in an edible grasshopper (Womeni *et al*., 2009). Such fats support healthy growth in infants and children (Michaelsen *et al*., 2009).

**Carbohydrates and chitin.** Carbohydrates ranged from about 6.7% in a stink bug to roughly 16% in cicadas (Raksakantong *et al*., 2010), much of it as chitin, which may help lower blood cholesterol (Burton & Zaccone, 2007). Insect polysaccharides might also support immunity (Sun *et al*., 2007).

**Minerals and vitamins.** Edible insects can supply iron, zinc, copper, manganese, calcium and phosphorus, with different species excelling at different minerals (Van Huis *et al*., 2013). That matters because iron deficiency is a major problem among women in developing regions, especially pregnant women in Africa (Orr, 1986). Nigerian studies also report appreciable vitamins A, B2 and C (Banjo *et al*., 2006; Igwe *et al*., 2011).

**Table 1. Selected minerals and vitamins in edible insects and what they do in the body**

| Nutrient | Role in the body | Insect highlighted |
|---|---|---|
| Iron | Acts with other trace minerals as an antioxidant and enzyme helper; shortage is common among women in developing regions | Axayacatl |
| Zinc | Supports immunity and, alongside magnesium and selenium, helps guard against stunted growth and immune problems | Cricket |
| Copper and manganese | Antioxidants and enzyme cofactors that strengthen the immune system | Mealworm (copper); cricket (manganese) |
| Magnesium | Needed for over 300 body reactions; steadies the heartbeat, supports muscles and nerves, and helps regulate blood sugar | Beetle larvae scored highest in Nigerian analyses |
| Vitamins A, B2 and C | A supports vision, B-group vitamins form parts of coenzymes, and C works as an antioxidant | Termites, beetles, grasshoppers, moths and butterflies analysed in Nigeria |

Tiencheu & Womeni (2017)

**Minilivestock: Farming small to think big**

Land, water and energy are dwindling and conventional livestock draw heavily on all three (Pimentel, 2004). Feed crops occupy land that could grow human food (Steinfeld *et al*., 2006). One estimate says livestock consume 77 million tons of human-edible protein to yield 58 million tons (Ramos-Elorduy, 2008).

Insect rearing looks leaner. It needs little space (Pimentel, 1980) and little water and many edible species do not compete with people for food (Tiencheu & Womeni, 2017). Hence the nickname "minilivestock" (Paoletti & Dreon, 2005). Insects are also nature's recyclers. Fly maggots and beetle larvae devour carcasses and about 400 dung beetle species help break down manure, releasing nutrients that improve soil fertility (Tiencheu & Womeni, 2017). Black soldier fly larvae can turn manure and organic waste into animal feed (Diener *et al*., 2009; Myers *et al*., 2008). Valuing insects as food could even encourage habitat protection (Steinfeld *et al*., 2006).

**More than a meal: Medicine and markets**

Traditional healers use insects against fever, scabies, epilepsy, bronchitis and dog bite, and to boost milk flow in nursing mothers (Tango, 1981). Laboratories are taking note: pierisin, from cabbage butterfly pupae, is toxic to human stomach cancer cells and cecropin acts against lymphoma and leukemia cells (Srivastava & Gupta, 2009). These are early leads, not cures.

Insects feed livelihoods too. Families in Zimbabwe, Nigeria, South Africa, Ivory Coast and Zambia earn a fair income selling them (Agbidye *et al*., 2009; Balinga *et al*., 2004). Women and children often gather them from bushland and farms for local markets, and some reach city restaurants or export (Chavunduka, 1975; Fasoranti & Ajiboye, 1993), though disorganised market chains hold the trade back (Tiencheu & Womeni, 2017).Other products add value: silk, with output above 90,000 tons (Yong-woo, 1999); carmine, a red dye used in food, textiles and pharmaceuticals; resilin, an elastic protein used to repair arteries (Elvin *et al*., 2005); and honey, propolis, royal jelly and venom used on wounds and burns (Van Huis, 2003).

**Hurdles ahead and the road forward**

Promise alone will not put insects on more plates. Tiencheu and Womeni (2017) name four priorities: more nutritional data, since patchy information weakens consumer confidence; side-by-side comparison of insect and livestock farming to see which harms the environment less; clearer evidence of insects' socioeconomic role in food security; and legal frameworks that encourage investment and trade.

**The final bite**

Edible insects pair high-quality protein and essential amino acids with healthy fats, minerals and vitamins and add medical, commercial and ecological value (Tiencheu & Womeni, 2017). For a world still struggling with hunger, that deserves serious attention from scientists, governments and aid programs. The next great protein source may already be hopping through the grass.

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# CAN WORMS EAT PLASTIC? THE SCIENCE OF INSECTS, GUT MICROBES AND PLASTIC WASTE

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Imagine opening a bag of grain from your pantry and finding a neat hole chewed through the packaging. For most of us, that is a nuisance. For a handful of scientists, it turned out to be the start of one of the most unexpected stories in environmental research: the discovery that some insect larvae can eat plastic and that the microbes living in their guts may help them digest it.

The idea is not entirely new. Entomologists noticed back in the 1950s that stored-product insects could bore through packaging films (Gerhardt & Lindgren, 1954) and a short report in the 1960s described moth larvae damaging polythene sheeting (Whalley, 1965). At the time, the concern was protecting food not cleaning up the planet. It took several more decades before anyone asked a bolder question: what if the insects are not just damaging plastic, but actually breaking it down?

**Why plastic is such a stubborn problem**

Humans had produced roughly 8,300 million tonnes of virgin plastic by 2017 and only a small share of it has been recycled or burned (Geyer *et al.,* 2017). Another estimate suggests that merely around 9% of all plastic ever made has gone through recycling (Nikiema & Asiedu, 2022). The rest lingers in landfills, soils and oceans, slowly crumbling into microscopic fragments. Polyethylene, the plastic behind shopping bags and food wrap, is a good example of why nature struggles with it. Its backbone is a long chain of very stable carbon bonds, it is extremely water-repelling and its molecules are far too big to slip into a microbial cell (Yang *et al.,* 2014). For decades, the scientific consensus was that ordinary microbes could barely touch it unless sunlight or heat had already weakened the material first.

**The waxworm hunch that started a field**

In 2014, a Chinese-American research team noticed that the larvae of the Indian meal moth, commonly called waxworms, were chewing holes in polyethylene packaging. They wondered whether the larvae's gut bacteria might be doing some of the work. They collected gut contents, grew them on polyethylene as the only food source, and isolated two bacteria, *Enterobacter asburiae* and a *Bacillus* strain.The evidence they assembled was unusually thorough. The bacteria formed living biofilms on the film, made its surface less water-repellent and carved pits and cavities into it. Chemical tests revealed new carbonyl groups, a typical fingerprint of oxidation. Over 60 days, the two strains reduced the weight of plastic films by about 6% and 11% and the leftover polymer chains were measurably shorter (Yang *et al.,* 2014).

**Mealworms and the carbon trail**

A year later, the same group turned to yellow mealworms, the larvae of the darkling beetle *Tenebrio molitor*. In a month-long trial, 500 larvae consumed about a third of a block of polystyrene foam, the material often called Styrofoam. Roughly 48% of the carbon they swallowed was exhaled as Carbon dioxide and the remaining plastic in their droppings had shorter chains and oxidised surfaces. Experiments using Polystyrene tagged with a heavy carbon isotope proved that the plastic's carbon really ended up as $CO_2$ and was even built into the larvae's body fat (Yang *et al.,* 2015a).

A companion study delivered a second key lesson. When the mealworms were fed antibiotics, their ability to digest polystyrene faded, which pointed to gut bacteria as essential partners (Yang *et al.,* 2015b). The beetle larva, in other words, behaves like a tiny bioreactor in which host and microbes work together.

**Waxworms return, with a controversy**

In 2017, a research team reported that larvae of the greater wax moth, *Galleria mellonella*, could eat polyethylene film at a remarkable pace (Bombelli *et al.,* 2017). Because these caterpillars normally feast on beeswax, which is also made of long hydrocarbon chains, scientists suspected that the same biochemical toolkit might handle plastic. Genome work supports the idea that waxworms can process beeswax without relying on gut microbes (Kong *et al.,* 2019) and further experiments showed that the larvae can fully digest Polystyrene microplastics even when their gut flora is not the main player (Wang *et al.,* 2022).

The story took a dramatic turn in 2022, when a team identified proteins in waxworm saliva that appeared able to oxidise Polyethylene within hours at room temperature (Sanluis-Verdes *et al.,* 2022). Follow-up work described the structures of these proteins, named Demetra, Ceres, Cibeles and Cora (Spínola-Amilibia *et al.,* 2023). The excitement was tempered in 2024, when an independent group reported that it could not reproduce the plastic degrading activity of one of the enzymes and suggested the original signals may have been misread (Stepnov *et al.,* 2024). Science, as usual, is still sorting out the details.

Microbes remain part of the picture too. In waxworms fed polyethylene, excretion of a breakdown product was reduced after antibiotic treatment, hinting that bacteria contribute even when the host has its own tools (Cassone *et al.,* 2020).

**Table 1. A short timeline of insect-and-plastic research**

| Year | What happened | Why it mattered |
|---|---|---|
| 1954 | Stored-product insects shown to penetrate packaging films (Gerhardt & Lindgren, 1954) | First sign that insects can damage synthetic materials |
| 1965 | Moth larvae reported to damage polythene (Whalley, 1965) | Early hint that larvae chew polyethylene |
| 2014 | Plastic-degrading bacteria isolated from waxworm guts (Yang *et al.,* 2014) | Linked insect guts to polyethylene breakdown |
| 2015 | Mealworms shown to mineralise polystyrene (Yang *et al.,* 2015a) | Isotope tracing proved plastic carbon becomes CO2 |
| 2017 | Waxworms observed eating polyethylene (Bombelli *et al.,* 2017) | Brought the topic to the public's attention |

| Year | What happened | Why it mattered |
|---|---|---|
| 2022 | Salivary enzymes proposed for polyethylene oxidation (Sanluis-Verdes *et al.,* 2022) | Suggested the insect itself, not only microbes, can attack plastic |
| 2023 | Mealworms break down PET extremely quickly (He *et al.,* 2023) | Showed speed rivalling the best-known PET-eating bacterium |
| 2024 | Replication doubts raised about one saliva enzyme (Stepnov *et al.,* 2024) | Reminder that the mechanisms still need confirmation |

**Many larvae, many plastics**

The cast of characters has since grown well beyond waxworms and mealworms. Superworms, the larvae of *Zophobas atratus*, have been reported to consume roughly four times as much Polystyrene per day as mealworms (Yang *et al.,* 2020). Dark mealworms (*Tenebrio obscurus*) also chew through polystyrene foam (Peng *et al.,* 2019) and a darkling beetle called *Plesiophthalmus davidis* survived on Styrofoam alone while harbouring a polystyrene-degrading gut bacterium (Woo *et al.,* 2020). Even the larvae of the fall armyworm carry a gut bacterium able to break down polyvinyl chloride (Zhang *et al.,* 2022).

The range of plastics is just as striking. In mealworms, researchers have documented activity on Polyethylene (Brandon *et al.,* 2018), Polyvinyl chloride (Peng *et al.,* 2020), and Polyethylene terephthalate, the plastic of drink bottles. In that last case, more than 70% of a commercial PET sample was degraded within about 12 to 15 hours, which on a half-life basis was dramatically faster than the celebrated bottle-eating bacterium *Ideonella sakaiensis* (He *et al.,* 2023; Yoshida *et al.,* 2016).

The larvae are not the only candidates. A cockroach species was reported to digest up to 46.6% of ingested polystyrene within a day (Li *et al.,* 2024), and a trio of yeasts taken from termite guts was shown to break down polyethylene (Elsamahy *et al.,* 2023). These findings hint that adult insects, too, might become plastic-eaters.

**Table 2. Plastic-eating insects at a glance**

| Insect (common name) | Plastics reported | Highlights |
|---|---|---|
| *Plodia interpunctella* (Indian meal moth) | Polyethylene | Source of the first polyethylene-degrading gut strains (Yang *et al.,* 2014) |
| *Galleria mellonella* (greater wax moth) | Polyethylene (Bombelli *et al.,* 2017); polystyrene (Wang *et al.,* 2022) | Saliva proteins and gut bacteria both implicated; some enzyme claims disputed (Sanluis-Verdes *et al.,* 2022; Stepnov *et al.,* 2024) |
| *Tenebrio molitor* (yellow mealworm) | Polystyrene (Yang *et al.,* 2015a); polyethylene (Brandon *et al.,* 2018); PVC (Peng *et al.,* 2020); PET (He *et al.,* 2023) | About 48% of ingested polystyrene carbon released as CO2; gut bacteria essential for polystyrene (Yang *et al.,* 2015a, 2015b) |
| *Tenebrio obscurus* (dark mealworm) | Polystyrene | Confirmed polystyrene chewing alongside yellow mealworms (Peng *et al.,* 2019) |

| Insect (common name) | Plastics reported | Highlights |
|---|---|---|
| *Zophobas atratus* (superworm) | Polystyrene | Higher polystyrene intake per day than mealworms (Yang *et al.,* 2020) |
| *Plesiophthalmus davidis* (darkling beetle) | Polystyrene | Lived on foam alone; polystyrene-degrading *Serratia* isolated (Woo *et al.,* 2020) |

**A partnership between host and microbe**

What emerges from these studies is a picture of teamwork. The mouthparts chew plastic into smaller pieces, digestive juices and enzymes begin chemical modification and gut microbes continue the job. Which partner leads seems to depend on the species and the polymer: antibiotics cripple polystyrene digestion in mealworms (Yang *et al.,* 2015b), whereas waxworms appear to rely more on their own biochemistry (Kong *et al.,* 2019; Wang *et al.,* 2022).

The idea of host-microbe cooperation also changes how scientists define biodegradation. Traditionally, the word described what bacteria and fungi do. Insects add a new layer, because their tissues, enzymes and microbial passengers act as a single system (Yang *et al.,* 2024).

**The reality check**

Before anyone pictures worm farms replacing recycling plants, a few cautions are in order.

**Plastic is poor food.** Waxworms fed only Polyethylene often lose weight and die within days, so they usually need a supplementary diet to stay healthy (Lou *et al.,* 2020).

**Breakdown is not always complete.** In mealworms fed PVC, about two-thirds of the swallowed plastic was altered, yet very little chlorine was released in simple inorganic form, with much of it ending up in chlorinated organic by-products and the larvae failing to complete their life cycle on that diet (Peng *et al.,* 2020).

**The economics and carbon maths are tough.** One assessment estimated that degrading a single tonne of polyethylene with waxworms or mealworms would need several tonnes of larvae, take more than a month, cost over 300 euros, and emit at least four tonnes of $CO_2$, which is more than incineration would release (Billen *et al.,* 2020). On a smaller scale, a study of surgical masks calculated that about 100 mealworms would need around 138 days to consume one mask (Gicole *et al.,* 2024).

**Safety questions remain.** Chewing breaks plastic into smaller particles, a process that has been tracked in mealworms fed Polystyrene and Polyethylene foams (Peng *et al.,* 2023), so further safety testing is still needed before larvae or their droppings are considered for animal feed.

**Where the research is heading**

The most promising route may not involve live insects at all. If scientists can pin down the exact enzymes and microbes responsible, those tools could be produced in laboratory cultures, engineered for greater speed and applied in controlled reactors. Recovered building blocks might even be turned into useful products. Researchers are also hoping to learn how gut microbial communities and host genes cooperate, so that the insect gut can be imitated rather than farmed (Yang *et al.,* 2024). Recent overviews of the field agree that although the topic is young, the number of species and mechanisms uncovered keeps climbing (Vital-Vilchis & Karunakaran, 2025).

**The bottom line**

A grain pest chewing through a packet in 2014 set off a decade of surprising discoveries. Waxworms, mealworms, superworms and their relatives have shown that even stubborn plastics can be oxidised, shortened and, at least partly, turned into carbon dioxide and body tissue. The technology is far from ready for the real world and some headline claims are still being tested. Even so, the insects have given scientists a new set of clues, and those clues may help us design faster, cleaner ways to deal with the plastic we have already made.

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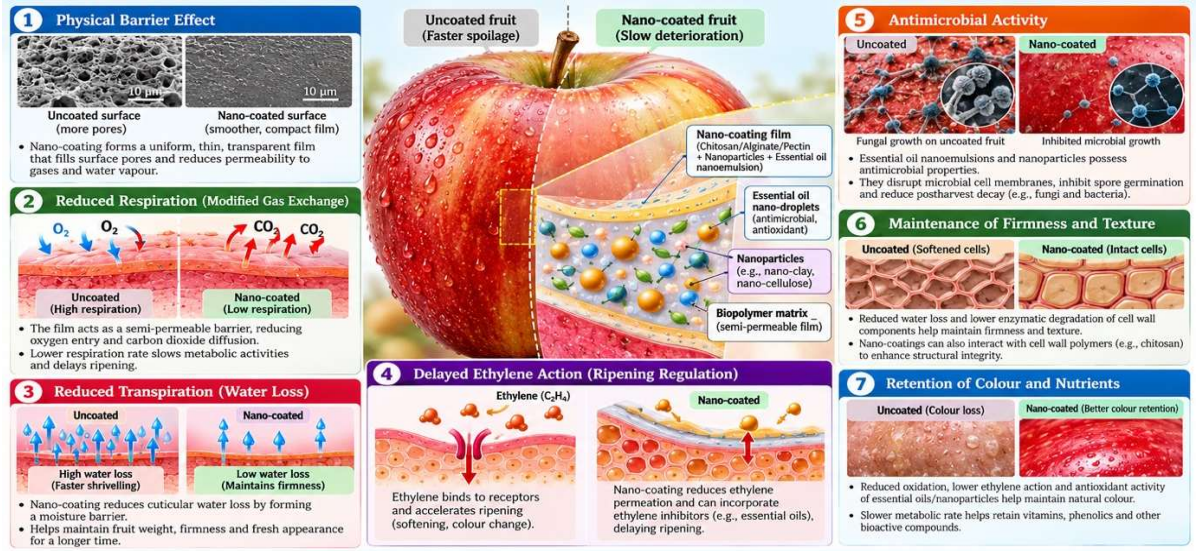
# AI-ASSISTED PREDICTION OF FRUIT SHELF LIFE USING INTELLIGENT PACKAGING, NON-DESTRUCTIVE QUALITY SENSORS AND EDIBLE NANO-COATINGS

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Fruits give us vitamins and minerals, dietary fibre, antioxidants, and numerous health promoting phytochemicals, an essential piece to a wholesome and balanced diet. Not only for their nutritional value, fruit production is also a major factor in food security, employment in rural areas, profitability of farms and the value chains of agricultural activities. But the fruits are a perishable biological product and post-harvest physiological and biochemical changes are rapid, thus causing significant qualitative and quantitative losses during handling, storage, transport and marketing of these products. The length of the shelf-life is essentially influenced by the Arabidopsis thalasiana primary metabolism processes triggered by postharvest respiration and transpiration, moisture losses, ethylene mediated ripening process, enzymatically driven degradation, microbial spoilage and mechanical damage involving post-harvest operations. These processes induce softening, colour changes, nutrition loss, decay and marketability losses.

The classical methods of shelf-life determination are based on periodic visual examination, destructive physio-chemical analysis and on the storage duration assessment. These methods are time consuming, subjective and are not always suitable to capture a real time quality change. Hence, the need for fast, non-destructive, continuous and predictive post-harvest monitoring technologies is growing. Artificial intelligence has great potential for analysing complex data derived from sensors and environmental factors and forecasting ripening behaviour, quality loss and remaining shelf life. Completed with non-destructive sensors, intelligent packaging, and edible nano-coatings, artificial intelligence can help to manage quality control through data insight, slow down fruit deterioration, optimize storage environment, and significantly reduce fruit losses after harvest.




**Mechanism of Action of Nano-Coatings on Fruits**

**Ripening and Senescence Dynamics**

The physiological, biochemical and structural changes which occur during ripening and senescence mark the interaction of coordinated events which control fruit shelf life. These fruits are climacteric fruits which show a sudden upsurge in respiration and ethylene production whereas non-climacteric fruits like grape, citrus and strawberry do not show much postharvest ethylene response. These differences play a significant role towards storage behavior and deterioration rate.

**Physical and Biochemical Quality Indicators**

Main physical symptoms are weight loss, firmness loss, shrinkage, colour development and surface defects, all of which are related to the loss of water, softening of the tissue and degradation of the membrane. Biochemical changes: change in total soluble solids, titratable acidity, pH, sugars, organic acids, antioxidants and phenolic compounds. These parameters define the degree of sweetness, acidity, nutrition and acceptability to the consumers.

**Physiological, Microbial, and Environmental Factors**

Physiological indicators to monitor metabolic activity and residual storage capacity include respiration rate, ethylene evolution and transpiration. At the same time, microbial growth will lead to decay and tissue degradation. These processes are mainly controlled by environmental factors such as temperature, relative humidity, oxygen, carbon dioxide and the length of storage. The assessment of fruit deterioration can be done by integrating several physical, biochemical, physiological, microbial and environmental attributes because no single attribute is sufficient to represent it. Based on this multidimensional assessment, intelligence monitoring of the quality and artificial intelligence-based prediction of the remaining marketable life can be realized more reliably.

**Non-Destructive Quality Sensors for Real-Time Fruit Monitoring**

**Need for Non-Destructive Quality Evaluation**

Non-destructive sensing technologies are gaining in significance in postharvest fruit management as the alternative traditional analytical techniques involve sample extraction of flesh, the use of chemical reagents, costly laboratory instruments and destroy the endogenetic commodity being tested. Non-destructive methods on the other hand, allow for rapid, repeatable and real-time evaluation, maintain marketability of the fruit and provide for continuous quality monitoring during storage and supply.

**Optical and Spectroscopic Sensing**

External features including surface defects, bruising, shape, size and colour are usually assessed with computer vision or RGB imaging. Near-infrared spectroscopy (NIR) is an analysis technique that makes it possible to estimate various parameters of the internal quality such as soluble solids, moisture, firmness, and maturity by measuring the absorption of light. Spatial and spectral data are also fused in hyperspectral and multispectral imaging, allowing simultaneous analysis of external and internal fault detection, physiological conditions and compositional changes.

**Chemical, Mechanical, and Biosensing Approaches**

Electronic nose systems capture signals of VOC characteristics related to ripening and spoilage while electronic tongues measure taste-related characteristics by electrochemical responses. Acoustic, ultrasonic, dielectric and firmness sensors give information related to the structure of tissues, elasticity and mechanical integrity. Biosensors can detect microbial contamination, enzymatic activity and biochemical markers. Dynamic monitoring of the storage conditions further supports

environmental sensors for temperature, relative humidity, oxygen (O2), carbon dioxide (CO2) and ethylene.

**Sensor Fusion for Improved Prediction**

There are advantages and drawbacks to each sensing technique in terms of cost, sensitivity, calibration, depth of penetration and complexity of operation. Hence, fusion of multiple complementary sensor technologies is important for obtaining more robust and accurate estimation of fruit quality. Combination of multimodal sensor with artificial intelligence can greatly enhance the real time sensing and prediction of ripening stage, ripening deterioration rate and remaining shelf life.

**Intelligent and Smart Packaging for Monitoring Fruit Freshness**

**Conventional, Active, Intelligent, and Smart Packaging**

Conventionally, most packaging systems are used to give only protection and containment to the product, while active packaging systems are aimed at interacting with the package environment to accomplish the purposes of moisture control, antimicrobial action and ethylene scavenging to enhance the shelf life. Intelligent packaging passively senses the product without changing it, and smart packaging refers to the packaging which combines the sensing, communication and digital technologies and can be used in real-time product quality sensing and traceability.

**Freshness Monitoring Indicators and Sensors**

Time–temperature indicators can be helpful for highly perishable fruits like strawberries, grapes and berries since they can show the amount of temperature abuse sustained during transit and storage periods. Freshness and ripeness indicators monitor changes related to volatile compounds, respiration and maturation processes e.g. ethylene-responsive indicators are used to monitor ripeness of banana, mango, avocado and tomato. O2/C02 sensors are especially useful when apples, cherries, and fresh-cut fruits are packaged in modified-atmosphere. In a similar manner, the pH-sensitive colorimetric indicators can be used to determine biochemical transformations that take place during acid formation and microbial spoilage.

**Biosensors and Digital Connectivity**

A biomass induced Packaging can be used to detect the presence of microbial contamination, metabolites or specific biomarkers of spoilage. Through RFID, NFC, QR codes or IoT, a storage history, temperature, and quality information can be exchanged across the supply chain. Smart labels, for example, on blueberries or table grapes could give a retailer details on the conditions of the packaging and the remaining shelf life.

**Integration with Artificial Intelligence and Key Challenges**

With intelligent packaging generating continuous data, this information together with AI models can be used to predict the freshness states of the fruits, deterioration rate and the optimum marketing times. But, its wide commercialization is limited by the cost of the sensor, stability of calibration, safety for food contact, reliability of signal, recyclability, and the need for large-scale manufacturing. Thus, biodegradable and stable packaging solutions will be needed that are environmentally friendly, sustainable, low-cost, and that will provide full digitization, and this will be required by future packaging systems and for real world fruit supply chains.

**Edible Nano-Coatings for Extending Fruit Shelf Life**

Edible Coating – Thin coating on fruit which is edible, can reduce moisture loss, affect gas exchange and protect against microbial deterioration. The most commonly used coating material is chitosan,

besides alginate, pectin, starch, cellulose derivatives, protein based, and lipid based compounds. This can be further boosted by the use of nanomaterials, nano emulsion or bioactive compounds with good barrier, antimicrobial and antioxidant properties.

**Nano emulsions and Nanocomposite Systems**

The nano emulsions synergizing oil and compounds from cinnamon, clove, lemongrass, or thyme extract have antimicrobial and antioxidant activity. Here the process explanation is needed, essential oils disperse into nanoscale droplets with the help of the emulsifiers, this enhances the control of essential oils, their stability, and surface-covering. For instance, coatings of nano emulsion of chitosan have been studied for strawberries and grapes to inhibit fungus growth and slow the ripening process. Nanocomposites can contain nano level cellulose, clay, or other GRAS nano bilayer/encapsulating materials for enhanced barrier properties against gases or moisture.

**Mechanisms of Shelf-Life Extension**

In this sub-point it is particularly crucial to explain the process. After application the coating becomes a semi-permeable layer which blocks influx of oxygen and hinders access of carbon dioxide, and this slows down respiration and transpiration. Reduced plant metabolism may lead to a slower ethylene mediated ripening process, having the effect of keeping fruits firmer, preventing colour change and normally reducing nutrient degradation. Such coatings may retard ripening in mango and banana, weight loss in apple and guava and surface spoilage in citrus, strawberry and grape.

**Safety and Commercial Considerations**

Even though they promise to be of great value, nano-coatings should be carefully assessed for nanoparticle migration, toxicity, biodegradability, food-contact safety, regulatory compliance, and acceptance by consumers before they can be put into use on a large scale. Safe, low-cost, transparent and easily applicable formulations are needed for commercial success.

**Dynamic prediction of fruit shelf life using Artificial Intelligence**

These technologies are used to process the complex postharvest data such as temperature, humidity, colour, firmness, gas composition, ethylene production, spectral features, microbial indicators and duration in storage. The regression models are applicable in a simple relationship, and gradient-boosting and Random Forest algorithms determine important predictors of deterioration. Support Vector Machines (SVMs) are used for classification of freshness and ripening stage whereas Artificial Neural Networks (ANNs) are used here to model some complex nonlinear relations. CNNs process the fruit images and classify the fruit images according to colour altering, bruising, fungus and infections, surface defect, and ripeness. In the case of the time series sensor data, models such as RNN and LSTM are more relevant. There is a combination of data from the different sensors: imaging, spectroscopy, electronic noses, intelligent packaging and environmental sensors. By integrating with IoT, continuous tracking of cold chain can be achieved, and real time alerts can be generated. In future, it could be possible to simulate fruit quality under different storage conditions in a digital-twin system, which would allow predictive management, minimize post-harvest losses and enhance supply-chain efficiency.

**Conclusion and Future Prospects**

Incorporating artificial intelligence (AI), non-destructive sensing, edible nano-coatings, and intelligent packaging can bring postharvest management in fruits from a reactive approach of

detection to a predictive and preventative quality control approach. Intelligent packaging adapts to the continuous temperature, humidity and gas changes, and monitors ripening and freshness, and non-destructive sensors rapidly determine the physical biochemical and physiological quality without affecting fruits. Edible nano-coatings provide additional benefits in prolonging the shelf life by limiting moisture loss, respiration, oxidation and microbial deterioration. By incorporating information on imaging, spectroscopy, indicating packaging, environmental sensors and physiological measurements, AI-based systems can be used to predict remaining shelf life, spoilage risk, and optimum storage, transport, processing and marketing decisions. This potential future research should focus on the use of low-cost portable sensors, standardized and different data sets, explainable AI, biodegradable and food-safe nano based materials, smartphone based diagnostics, and low-cost IoT systems. Field validation will be important during storage, transport, and retail trade to develop safe, scalable, interoperable, and farmer-accessible technologies that will provide real-time actionable predictions of quality.

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# THE SCIENCE OF DRYLAND AGRICULTURE: LIVING WITH NATURE, MANAGING CLIMATIC UNCERTAINTY AND SUSTAINING AGRICULTURAL LIVELIHOODS

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Dryland agriculture represents one of the most challenging frontiers of agricultural science, where production depends predominantly on rainfall, an inherently variable resource characterized by uncertainty in its occurrence, distribution, intensity and duration. Unlike irrigated agriculture, dryland farming must operate within the opportunities and constraints imposed by prevailing climatic conditions. The fundamental philosophy of dryland agriculture is not to conquer nature, but to understand its dynamics, adapt to its variability and optimize the use of available natural resources. It extends beyond crop cultivation without irrigation, encompassing the integrated management of weather, climate, soil, water, crops, livestock, natural vegetation and human resources to sustain agricultural productivity and livelihoods.

Dryland agriculture is neither merely conventional agronomy nor soil science; it is an integrated science of weather, climate and agricultural production, drawing upon agroclimatology, hydrology, crop physiology, ecology and resource management. Its ultimate objective is to align agricultural practices with climatic opportunities, conserve every available unit of water and build resilient farming systems capable of sustaining production under increasing climatic uncertainty.

Agronomy and soil science provide essential technological foundations. However, their effectiveness under rainfed conditions depends considerably on prevailing and anticipated weather. The challenge is to integrate these disciplines with agricultural meteorology, climatology, hydrology, crop physiology, agricultural engineering and socioeconomic considerations. The ultimate purpose is not merely to increase agricultural production, but to ensure its stability, conserve natural resources and sustain the livelihoods of farming communities.

## 1. The Fundamental Philosophy of Dryland Agriculture

The central philosophy of dryland agriculture may be expressed as “To maximise the productive use of available rainfall and to minimise the risks arising from climatic uncertainty, conserve the natural resource base and ensure the stability of agricultural production and farmers ’livelihoods”.

This philosophy rests on five fundamental principles.

**1.1 Adaptation rather than domination:** Agricultural practices must be adjusted to prevailing climatic conditions, soil characteristics and water availability rather than imposing production systems unsuitable for local environments.

**1.2 Conservation rather than exploitation:** Rainfall, soil moisture, soil fertility and vegetation must be conserved to sustain productivity over successive seasons.

**1.3 Stability rather than maximum yield alone:** Dependable production across several years may be more valuable than exceptionally high yields during favourable seasons followed by severe crop losses during drought years.

**1.4 Diversification rather than dependence:** Integration of crops, livestock, trees and supplementary enterprises reduces vulnerability to climatic variability.

**1.5 Resilience rather than short-term profitability:** Agricultural systems must withstand climatic shocks, recover from unfavorable seasons and maintain long-term livelihood security.

These principles establish dryland agriculture as a science of adaptation, conservation, risk management and sustainable production.

**2. Dryland Agriculture Is Not Routine Agronomy or Soil Science**

Agronomy primarily deals with crop cultivation, field management and production technologies. Soil science examines soil properties, fertility, moisture retention and nutrient dynamics. Both disciplines are indispensable components of dryland agriculture, but neither independently explains the complexity of farming under uncertain rainfall.

For example, a recommended crop variety may perform satisfactorily under favourable rainfall but fail when sowing is delayed. Fertiliser application may increase yields when soil moisture is adequate but become ineffective or economically risky during drought. Similarly, a crop may receive sufficient seasonal rainfall yet suffer severe moisture stress when prolonged dry spells coincide with flowering or grain development.

These examples demonstrate that agricultural technologies cannot be evaluated independently of weather conditions.

Agricultural meteorology provides the scientific framework for understanding the interactions between atmospheric conditions and agricultural production. Climatology establishes rainfall probabilities and climatic limitations. Hydrology explains water movement and availability. Crop physiology describes plant responses to environmental stress. Agronomy and soil science provide management technologies, while economics and social sciences help determine their feasibility.

The science of dryland agriculture emerges from integrating these disciplines into a coordinated system. Its central concern is not simply identifying the best crop or cultivation practice, but determining which agricultural practice is appropriate, under what climatic conditions, at what time and with what degree of risk.

Thus, agricultural meteorology should occupy a central coordinating position within the interdisciplinary framework of dryland agricultural science.

**3. Climatic Water Balance: The Scientific Foundation**

The climatic water balance provides the scientific foundation for understanding dryland agricultural potential.

Annual rainfall alone cannot adequately describe the agricultural suitability of a region. Two locations receiving similar annual rainfall may differ considerably in crop productivity because of variations in rainfall distribution, evaporative demand, soil-water storage and growing-season duration. The important components include rainfall amount, intensity, frequency and distribution; potential evapotranspiration; soil-water storage capacity; runoff; drainage and crop-water requirements.

The essential question is not merely how much rainfall occurs, but how much water becomes available to crops, when it becomes available and how dependably it can satisfy crop requirements. A crop may receive adequate total rainfall but experience severe stress when dry spells coincide with critical growth stages. Conversely, moderate rainfall distributed favourably throughout the growing season may support satisfactory production. Climatic water balance analysis, soil-water budgeting and crop-water requirement assessment should therefore guide crop selection, sowing schedules, cropping intensity and conservation measures.

Rainfall is a climatic input, but its agricultural value depends on its timing, distribution, storage and productive utilisation.

**4. Agroclimatic Analysis and Crop Planning**

Dryland agricultural planning must begin with a systematic assessment of agroclimatic resources. Long-term rainfall records should be analysed to determine seasonal rainfall probabilities, onset and withdrawal of rainy seasons, length of growing periods, frequency of dry spells and occurrence of agricultural droughts.

Temperature, solar radiation and atmospheric evaporative demand must also be examined because they influence crop growth, development and water requirements.

Such analyses help identify suitable crops, varieties, cropping systems, sowing windows and alternative land-use options.

Areas with short growing periods may favour short-duration crops, pulses, millets or integrated crop–livestock systems. Regions with relatively dependable rainfall and greater soil-water storage may support more intensive cropping systems. Agricultural recommendations should therefore be based on agroclimatic suitability rather than uniform packages of practices developed without adequate consideration of local climatic differences.

**5. Incorporating Climate Predictions into Dryland Agriculture**

Traditional dryland agricultural planning relies heavily on historical climatic information. However, historical averages alone cannot adequately support decisions under changing climatic conditions. Advances in climate prediction provide opportunities to introduce anticipatory agricultural planning.

Seasonal climate outlooks may indicate the probabilities of below-normal, near-normal or above-normal rainfall and possible temperature anomalies. These predictions can support decisions concerning crop selection, cropping intensity, input procurement, water conservation and drought preparedness. When seasonal forecasts indicate an increased probability of deficient rainfall, agricultural institutions may recommend suitable short-duration crops, drought-tolerant varieties, reduced exposure to costly inputs and greater emphasis on moisture conservation.

When favourable rainfall probabilities are indicated, opportunities for appropriate crop diversification and improved productivity may be considered. However, seasonal forecasts are probabilistic rather than deterministic. Their accuracy varies across regions, seasons and prediction timescales.

Climate predictions should therefore complement long-term agroclimatic analysis rather than replace it. The objective is to develop alternative agricultural strategies corresponding to different possible climatic outcomes. This approach transforms climate prediction into climate-informed agricultural planning.

**6. Weather Forecasts and Dynamic Agricultural Management**

Weather forecasts provide an essential link between scientific information and day-to-day agricultural operations.

Medium-range forecasts can assist farmers in scheduling sowing, fertiliser application, intercultural operations, plant protection measures and harvesting.

Forecast rainfall may influence the timing of sowing and fertiliser application. Predictions of prolonged dry spells may justify moisture conservation measures or adjustments in crop management. Heavy rainfall warnings may support drainage preparation and protection of harvested produce.

Extended-range forecasts can provide additional guidance concerning likely rainfall and temperature conditions over subsequent weeks.

The greatest benefit arises when forecasts are translated into specific, timely and practical agricultural advisories. A forecast stating that rainfall is likely has limited agricultural value unless farmers understand what action should follow. An effective advisory should explain the expected weather, its likely agricultural implications, the recommended management response and the uncertainty associated with the forecast. The value of weather prediction lies not merely in forecasting atmospheric conditions, but in converting predictions into appropriate agricultural decisions.

**7. Integrating Climate and Weather Predictions across Timescales**

Dryland agriculture requires a coordinated prediction and decision-support system operating across different timescales. Long-term climatic information should guide land-use planning, crop suitability assessment and infrastructure development.

Seasonal predictions should support advance crop planning, input supply management and drought preparedness. Extended-range predictions should assist adjustments to cropping strategies and preparedness for emerging moisture deficits. Medium-range and short-range weather forecasts should guide field operations and immediate risk management.

Observed rainfall, soil moisture, crop conditions and satellite-based information should be used continuously to revise agricultural recommendations. The integration of these sources creates a dynamic agricultural management system in which decisions are progressively updated as the season develops. For example, a seasonal forecast may favour a particular crop, but delayed monsoon onset may subsequently require changes in sowing strategy. Later forecasts and observed soil moisture conditions may necessitate further adjustments. This process of continuous assessment and adaptation is central to climate-informed dryland agriculture.

**8. Contingency Planning and Risk Management**

Contingency planning is one of the defining characteristics of dryland agricultural science. Since rainfall cannot be controlled, agricultural systems must be prepared to respond to delayed onset, early withdrawal, prolonged dry spells, excessive rainfall and extreme temperatures.

Contingency plans should identify alternative crops, varieties, sowing windows and management practices for different rainfall situations. Such plans must be developed before the agricultural season and supported by arrangements for timely availability of seeds, fertilisers, machinery, labour and advisory services.

A scientifically sound contingency plan must also be operationally feasible. Recommending an alternative crop has little practical value if the required seed is unavailable when farmers need it. Therefore, contingency planning must connect agroclimatic analysis with institutional preparedness and agricultural logistics. The objective is not to eliminate climatic risk, which is impossible, but to reduce exposure, limit losses and improve recovery.

**9. Soil and Water Conservation Within an Integrated Framework**

Soil and water conservation is an essential component of dryland agriculture, but it should not be regarded as its complete scientific identity. Measures such as contour cultivation, mulching, conservation tillage, rainwater harvesting, appropriate land shaping and soil organic matter management can improve water infiltration, reduce runoff and enhance soil-moisture availability.

Their effectiveness depends on rainfall characteristics, soil properties, slope, cropping systems and management practices. Conservation technologies should therefore be selected through an integrated understanding of hydrological processes and agricultural requirements. The objective is not simply to conserve the maximum possible quantity of water, but to improve its availability and productive utilisation when crops require it. Soil and water conservation is most effective when combined with appropriate crop selection, timely operations and weather-responsive management.

**10. Diversified Farming Systems and Livelihood Security**

Dryland agriculture must extend beyond individual crop performance to the sustainability of entire farming systems. Dependence on a single crop exposes farmers to climatic, biological and market risks. Diversification through suitable combinations of cereals, pulses, oilseeds, fodder crops, livestock, agroforestry and supplementary enterprises can improve resilience. Integrated farming systems may also promote nutrient recycling, productive utilisation of crop residues and efficient use of available resources.

However, diversification should be based on agro-climatic suitability, resource availability, market opportunities and farmers ’capacities. The ultimate objective is not diversification for its own sake, but the creation of farming systems capable of maintaining reasonable income and productive capacity under variable climatic conditions. Livelihood security must therefore be recognized as a legitimate scientific and developmental objective of dryland agriculture.

**11. Reorienting Research and Agricultural Education**

Dryland agricultural research should move beyond isolated experiments on varieties, fertilisers, tillage and soil conservation towards integrated investigations of weather–soil–crop–management interactions. Research programmes should evaluate technologies under contrasting rainfall situations and assess performance over multiple seasons. Yield stability, water productivity, economic risk, resource conservation and recovery following drought should receive greater attention alongside conventional productivity measurements.

Crop simulation models, climatic databases, remote sensing, soil-moisture observations and decision-support systems can strengthen such investigations.

Research institutions should encourage closer coordination among agricultural meteorologists, agronomists, soil scientists, hydrologists, engineers, economists and extension specialists. Agricultural universities should recognise dryland agriculture as an interdisciplinary scientific field with agricultural meteorology occupying a central coordinating role. Teaching programmes should

include climatic water balance, rainfall probability analysis, weather forecasting, crop-weather relationships, drought assessment, contingency planning and climate-risk management. The effectiveness of research should ultimately be judged not only by technologies developed or publications produced, but by their contribution to production stability, farmer welfare and sustainable resource management.

**12. From Weather Uncertainty to Agricultural Resilience**

Dryland agriculture represents a scientific approach to living and producing within the opportunities and limitations of nature. Its fundamental challenge is not simply water scarcity, but uncertainty associated with water availability, distribution and agricultural effectiveness.

Agronomy, soil science and water conservation provide essential technological components, but the larger scientific framework must integrate weather, climate, crops, soil, water, management decisions and livelihood considerations.

Climate predictions and weather forecasts provide opportunities to transform dryland agriculture from a predominantly reactive system into an anticipatory and adaptive system. However, predictions acquire practical value only when supported by appropriate technologies, timely inputs, institutional coordination and effective communication with farmers.

Dryland agriculture should therefore be recognised not merely as the science of producing crops under limited rainfall, but as the integrated science of managing weather-dependent agricultural systems under climatic uncertainty.

Its guiding philosophy may be summarised as *"Produce according to the potential of nature, conserve resources for the uncertainties of tomorrow, anticipate climatic risks through scientific intelligence and protect the livelihoods of those who depend on the land."*

The true measure of success in dryland agriculture lies not in achieving maximum yields during favourable seasons, but in sustaining productivity, strengthening resilience and ensuring economic security for farming communities across the full spectrum of climatic variability—from years of abundance to seasons of adversity.

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# SEED ENDOPHYTES HELP CROPS FIGHT DISEASES AND ENVIRONMENTAL STRESS

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## Introduction

Agriculture today is facing many challenges. Farmers must deal with diseases, insect pests, drought, floods, poor soil, and changing weather conditions. At the same time, there is an increasing demand for reduced use of chemical fertilizers and pesticides which is crucial to the protection of human health and environment. So, scientists are searching for natural, eco-friendly solutions that can help make farming more sustainable. One promising solution is the tiny micro-organisms that are found inside plant seeds. These helpful microbes are known as seed endophytes. Seed endophytes can't be seen with the naked eye but they play an important role in helping plants to grow and be healthy and survive under difficult conditions. They are silent partners helping plants through their lives. In recent years, seed endophytes have attracted great attention in the research field, because of their potential to improve crop production in a natural and sustainable way.

## What are Seed Endophytes?

The word endophyte comes from the Greek words endo, meaning "inside," and phyte, meaning "plant." Endophytes are microorganisms, mainly bacteria and fungi, which live in the healthy tissues of plants without causing any disease. These microorganisms that are present in seeds are called seed endophytes. While microbes that reside only on the seed surface, seed endophytes are protected and live inside the seed tissues. As the seed sprouts, these helpful microbes grow along with the young plant, continuing to help it throughout its life. Seed endophytes have been reported to be present in many important crops *viz.*, rice, wheat, maize, soybean, chickpea, cotton, tomato, mustard, etc. Some of the most studied bacterial seed endophytes are *Bacillus*, *Pseudomonas*, *Enterobacter*, *Burkholderia*, *Azospirillum*, *Paenibacillus*, and *Microbacterium*. These bacteria help plants by fixing atmospheric nitrogen, solubilizing phosphorus, producing growth promoting hormones and protection against pathogens. Major groups of fungal endophytes include *Trichoderma*, *Penicillium*, and some non-pathogenic species of *Fusarium*. These fungi increase nutrient uptake, root growth, tolerance to environmental stress and suppress the harmful fungi that cause plant disease.

## How Do Seed Endophytes Enter the Seed?

Seed endophytes colonize seeds in many ways. Some microorganisms are transported from the mother plant into developing seeds through flowers and vascular tissues. Others take up the seed from the environment in which the seed develops. Once inside the seed they remain dormant until the seed begins to sprout. These microorganisms become active and colonize different parts of the growing seedling, including roots, stems and leaves, once water is absorbed and germination begins. The natural way enables beneficial microbes to be passed on to the next generation of plants, as parents pass on good traits to their children.

**Why Are Seed Endophytes Important?**

Seed endophytes are already inside the seed; they have a head start, and they can support the plant better than many microbes that are added to the soil later. The significance of these further increases in the changing climate conditions where crops are often exposed to drought, heat, flooding, salinity and nutrient deficiency.

**Protection Against Diseases:** Conventionally, farmers utilized chemical insecticides to combat various diseases. However, the excessive use of pesticides leads to environmental pollution, increased costs of production and resistant pathogens. Seed endophytes provide a natural alternative. Many good bacteria and fungi produce antimicrobial substances which inhibit the growth of organisms that cause disease. They compete with pathogens for food and space thus decreasing the chances of these pathogens infecting the plant. Some seed endophytes also induce the plant's own defense system. This is called induced systemic resistance and means that the plant is better able to resist attacks from pathogens in the future. These protective effects often translate into plants with beneficial seed endophytes suffering less disease and requiring less chemical treatment.

**Management of Insect Pests:** Some endophytes secrete substances toxic to harmful insects but harmless to plants, humans and beneficial organisms. Seed endophytes also reinforce the plant's own defense system. Insects trigger plants harbouring beneficial endophytes to ramp up production of defensive chemicals, leading to less insect feeding and lower crop loss. Some endophytes can even induce the plant to release certain volatile compounds which attract natural enemies of insect pests. These natural pest control mechanisms will reduce reliance on chemical insecticides and promote environmentally sound pest control. However, seed endophytes cannot replace insecticides in all cases but can be an important part of integrated pest management (IPM) programs.

**Boost Plant Growth:** Seed endophytes are known to produce plant growth hormones like auxins, gibberellins and cytokinins. These hormones stimulate germination of seed, formation of root and development of shoot. It helps in development of more powerful root system allows plants to take up more water and nutrients from the soil, resulting in more vigorous crop and better yields. Additionally, some endophytes make nutrients more available to plants by fixing atmospheric nitrogen or solubilizing phosphorus and mobilizing potassium in the soil.

**Making Sure Plants Survive Drought**: Drought is one of the biggest threats to agriculture worldwide. Less rain, less growth and less crop yield. Seed endophytes help plants survive drought in several ways. They help the roots grow better, so the plant can get water from deeper in the ground. Endophytes can also produce compounds that assist cells of plants in retaining water and reducing water loss. They also enhance the synthesis of protective compounds such as proline and antioxidants which are reduced in the damage caused by water deficiency. The result is greener, healthier, more productive plants even in water-stressed conditions.

**Salinity Tolerance:** Excess salt affects various processes like seed germination, root growth and nutrient uptake, etc. Some seed endophytes help plants to survive saline environments by maintaining the required balance of minerals inside the cells of plants. They help to diminish the destructive effects of sodium and increase the absorption of vital nutrients like potassium and calcium. This enables the plants to grow in moderately saline soils.

**Protection from Heat and Cold Stress**: Extreme temperatures are becoming more common, and that's what climate change means. High temperatures can damage plant proteins, reduce photosynthesis and reduce crop production. Low temperatures stunt plant growth and damage young seedlings. Seed endophytes produce protective proteins, antioxidants and stress related enzymes which help the plants to cope with temperature stress. These substances help protect against cellular damage and enable plants to recover more quickly from exposure to extreme weather.

**Flooding Stress:** Flooding starves the soil of oxygen, which in turn prevents the roots of plants from functioning properly. Some seed endophytes aid the plant to overcome temporary flooding by reducing stress hormones and enhancing root metabolism. Additionally, they aid in the quicker recovery of plants when floodwaters subside.

**Applications in Sustainable Agriculture**

The goal of modern agriculture is to produce more food while safeguarding the environment. In this regard, there are several practical applications of seed endophytes. One of the most promising applications is the development of microbial seed treatments Seeds can also be coated with selected beneficial endophytes prior to sowing. These microorganisms rapidly colonize the young plant when the seed germinates and provide long-lasting benefits. Seed endophytes may also reduce the use of chemical fertilizers by improving nutrient availability. Natural ability to fix nitrogen and solubilize phosphorus helps plants to get the vital nutrients naturally. Another major use is in biological disease control. Beneficial endophytes reduce plant pathogens, thereby reducing the need for synthetic fungicides and bactericides. Seed endophytes are valuable biological tools for growing healthy crops in organic farming, where the use of chemical inputs is restricted. They also promote the health of the soil by increasing beneficial microbial populations and adding to soil fertility over time. The transition of agriculture to environment-friendly practices is likely to make seed endophytes important components of biofertilizers and biopesticides.

**Role in Climate Smart Agriculture**

With increasing temperatures, erratic rainfall, droughts, floods and increasing soil salinity climate change is presenting serious challenges to agriculture. Farmers need new solutions that will help crops adapt to these changing conditions. Seed endophytes play a significant role in climate-smart agriculture as they improve plant resilience naturally. Plants containing beneficial endophytes are often more capable to survive periods of water shortage, extreme heat, cold temperatures and salt stress. These microbes also improve water-use efficiency, enabling crops to do more with less water. More efficient nutrient uptake allows crops to use fewer external inputs, thus producing fewer greenhouse gasses from fertilizer production and use. "Healthy plants with good microbial partners are more productive and bounce back faster from environmental stresses." Seed endophytes have the potential to increase food security under climate change by creating stability of crops under erratic weather. Their role is very much in line with climate-smart agriculture, which is about increasing productivity, building resilience and reducing environmental impacts.

**Future Directions and Challenges**

Despite this potential, there are still many obstacles to overcome before seed endophytes can be broadly adopted by farmers. One major challenge is the diversity of the endophytes. Which microorganisms can survive inside the seeds of a plant depends on the plant's type and the conditions of its environment. An endophyte that performs well in one crop or in one region may

not perform as well in another. Another challenge is to ensure viability of the beneficial microorganisms during seed storage and transport. Scientists are working on better formulations that keep endophytes alive and effective until planting. Performance on a large-scale field also needs to be evaluated further. Results achieved in laboratories and greenhouses do not always translate to farmers' fields because of differences in soil, climate and farming practices. Scientists are now using sophisticated technologies such as genomics, metagenomics, artificial intelligence and microbial engineering to find highly effective endophytes and understand their interactions with plants. Future efforts may also focus on breeding crop varieties that naturally support more beneficial seed microbiomes. Translating scientific discoveries into real solutions for farmers will require close collaboration between researchers, seed companies, extension workers and farmers.

**Conclusion**

Seed endophytes are tiny but mighty partners that work behind the scenes to support plant health from the very beginning of a plant's life. These beneficial microorganisms reside inside seeds, and help crops grow better absorb nutrients more efficiently resist diseases and insect pests and survive environmental stresses such as drought salinity flooding and extreme temperatures. Seed endophytes are one of the most promising biological resources in a world seeking sustainable ways to produce more food and use fewer chemical fertilizers and pesticides. They are useful tools for sustainable and climate-smart agriculture because of their potential for natural improvement of plant health. While research is still needed to address challenges with field performance, storage and commercialization, scientific advances in microbiology and biotechnology are rapidly improving our knowledge of these hidden plant partners.

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# MICROPLASTICS IN AGRICULTURAL SOILS: SOURCES, EFFECTS AND REMEDIATION STRATEGIES

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**Abstract**
Microplastics are plastic particles smaller than 5 mm. They are now found in farmland across the world, where they arrive with plastic mulch films, sewage sludge, compost, irrigation water, coated fertilisers and dust. Once in the soil they break down very slowly and can change soil structure, water movement, microbial activity and the growth of crops. Some effects look harmful, such as weaker soil aggregates and poorer earthworm health, while others, such as better aeration and higher plant biomass in short experiments, can be misleading. This article explains in simple terms where agricultural microplastics come from, what they do in soil, and which remediation options are available. It concludes that preventing entry at the source is the most dependable strategy, with biological and biochar-based methods still at the research stage.

**Keywords:** microplastics, agricultural soil, plastic mulch, soil health, biochar, earthworms

## Introduction

Plastic has become part of modern farming. Thin films cover the soil to save water and control weeds, pipes carry irrigation water, nets protect fruit and vegetables, and many fertilisers and seeds are coated with polymers. These materials are useful, but they do not disappear when the season ends. Sunlight, heat, tillage and soil organisms slowly break them into smaller and smaller pieces.

Fragments smaller than 5 mm are called microplastics (Yu *et al*., 2022). Because soil receives plastic from many directions and holds on to it, farmland is now regarded as an important store of these particles. Reviews report that microplastics are generally more abundant in agricultural soils than in urban soils (Yu *et al*., 2022). This has raised questions about soil health, crop growth and the possible entry of plastics into the food chain. Figure 1 gives an overview of the topics covered in this article.

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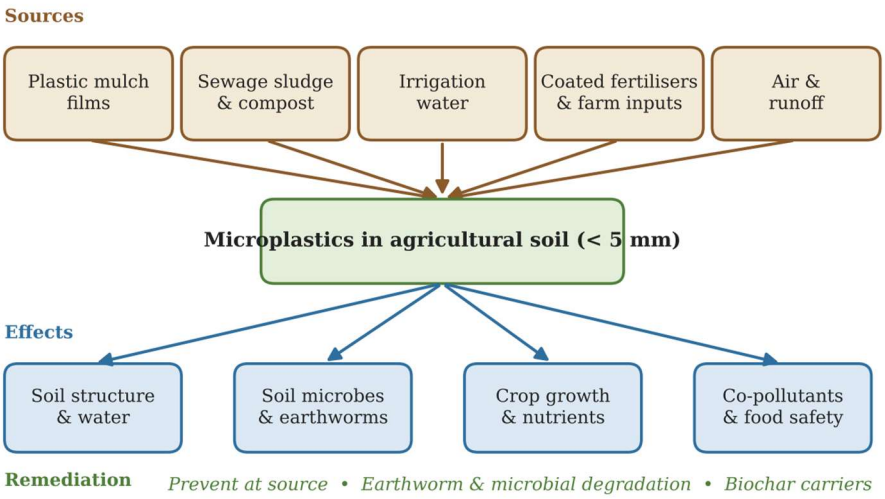



***Figure 1: Schematic of how microplastics reach agricultural soil, the main ways they affect it, and the remediation options discussed in this article***

**Where do microplastics in farmland come from?**

Microplastics reach soil as primary particles, which are made small on purpose, or as secondary particles formed when larger plastic breaks down. In agriculture, the main routes are summarised in Table 1.

**Table 1: Main sources of microplastics in agricultural soils**

| Source | How plastics reach the soil | Why it matters |
|---|---|---|
| Plastic mulch films | Films fragment under sunlight and tillage; pieces are left behind after harvest | Often described as the largest direct input in farmland |
| Sewage sludge and compost | Fibres and fragments from washing, cosmetics and household waste pass into biosolids and manure compost | Applied repeatedly to the same fields |
| Irrigation and floodwater | Treated or untreated wastewater and surface water carry particles to the field | Adds particles over the whole cropping season |
| Coated fertilisers and other inputs | Polymer-coated urea, pesticide containers, drip pipes and nets shed particles | Introduces plastics and additives with each application |
| Air and runoff | Dust, tyre and road wear and nearby litter settle on or wash into fields | Harder to control at farm level |

Plastic mulch film is widely regarded as the largest direct input. Non-biodegradable polyethylene film is cheap and effective, but it ages, tears and is rarely recovered completely, so fragments accumulate in the plough layer year after year (Liu *et al*., 2014; Huang *et al*., 2020). Sewage sludge and manure compost are the second major route. Microscopic fibres and particles that leave homes

with wastewater are not fully removed in treatment plants and end up in biosolids, which are then spread on land as a source of nutrients and organic matter (Rillig, 2012).

**What do microplastics do in the soil?**

Microplastics are not just inert litter. They sit among soil particles and can change how the soil behaves. Experiments with different shapes and types of plastic show that the outcome depends on the shape, the polymer, the dose and the soil itself (de Souza Machado *et al*., 2019; Lozano *et al*., 2021).

**Soil structure and water.** In one glasshouse study, all the plastic shapes tested reduced soil aggregation by roughly a quarter, probably because particles create weak points inside aggregates (Lozano *et al*., 2021). Fibres can hold water in the soil for longer, while films and foams can lower bulk density and increase pore space. Changes of this kind can alter aeration, water holding capacity and drainage (de Souza Machado *et al*., 2019).

**Plants.** Results are mixed. In the same experiment, plant biomass rose with every shape of plastic at doses of 0.1 to 0.4 per cent, with shoot mass increasing by about 27 per cent with fibres and about 60 per cent with films (Lozano *et al*., 2021; Figure 2). Other work found significant changes in plant biomass, root traits and tissue nutrient content, with polyester fibres and polyamide beads having the strongest effects on spring onion (de Souza Machado *et al*., 2019). A short-term gain in growth should therefore not be read as a benefit. It may reflect loosened soil while the underlying structure and biology are being disturbed.

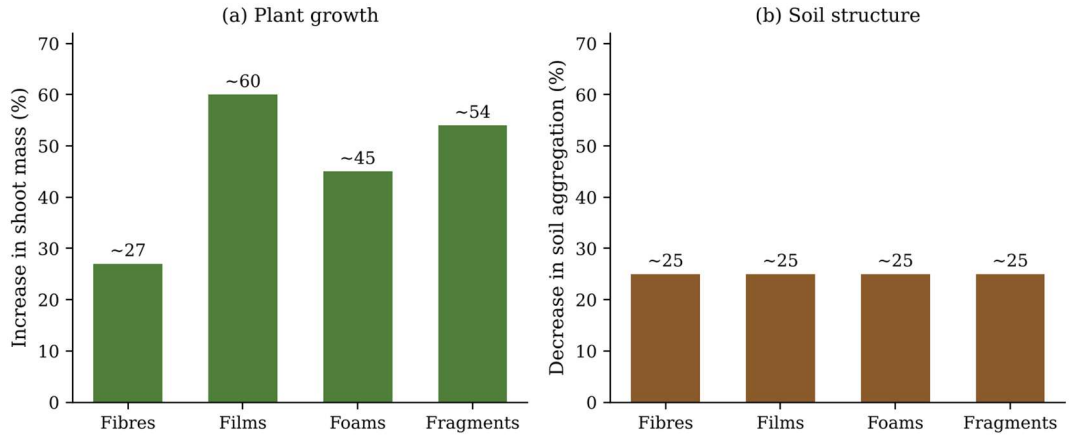



***Figure 2: Effects of different microplastic shapes on (a) shoot mass and (b) soil aggregation in a glasshouse experiment at 0.1 to 0.4% plastic. Approximate values as reported by Lozano et al., (2021); the study reports a decrease of about 25% in aggregation for all shapes together***

**Soil life.** Microbial activity and community composition can shift when plastics are added, and soil animals can be affected. In one trial, earthworms survived in soil containing 1 per cent microplastics but suffered high mortality when exposed to plastic alone, and they were able to ingest and fragment polyethylene particles in the gut (Wageningen University, 2022). Reviews also describe interactions with nitrogen cycling, where some plastics can change ammonium levels and ammonia loss (Guo and Zhu, 2025).

**Pollutants and food safety.** Microplastics can carry additives and can adsorb heavy metals and organic pollutants, so their presence may add to the combined burden of contaminants in soil (Yu

*et al*., 2022). Whether crops take up meaningful amounts of plastic and what this means for human health are still open questions, and current evidence is limited.

**Remediation and management strategies**

No single method can clean microplastics out of large areas of field soil, because the particles are tiny, mixed through the soil and chemically stable. Strategies are therefore best organised from prevention to cure.

**1. Prevent entry.** This is the most practical measure. Farmers can choose thicker mulch films that are easier to lift, remove all film after harvest, and avoid leaving torn pieces in the field. Sludge and compost can be screened or quality-tested before application, and wastewater treatment can be improved so fewer particles reach biosolids and irrigation water. Reducing plastic-coated inputs and using durable pipes and nets also lowers the load. Clear rules on film thickness, collection and recycling, and on the quality of sludge applied to land, would support these steps (Yu *et al*., 2022).

**2. Use biodegradable mulches with care.** Biodegradable films are promoted as an alternative, but they break down in soil only under suitable temperature, moisture and microbial conditions, and in the field their rate of breakdown is often lower than in laboratory tests (Sanchez-Hernandez *et al*., 2020). Until their full breakdown and effects on soil life are better understood, they should not be treated as a risk-free replacement.

**3. Biological approaches.** Soil organisms can help fragment and degrade plastics. Earthworms drag plastic into burrows, ingest it, and create habitats where microbes can multiply, and it has been proposed that adding earthworms or vermicomposting biodegradable plastics could speed up their breakdown (Sanchez-Hernandez *et al*., 2020). A 2025 microcosm study found that earthworms increased mass loss of biodegradable mulch film and enriched the microbial community associated with it (Environment International, 2025). Plastic-degrading bacteria and fungi are also being tested, but questions remain about how long they persist in soil and how they interact with native microbes.

**4. Biochar and organic carriers.** Biochar is a porous, carbon-rich material made by heating biomass. Reviews highlight it as a promising option because it can improve soil conditions and support plastic-degrading microbes and enzymes (Guo and Zhu, 2025). In mesocosm trials, biochar-based carriers for plastic-degrading microbial consortia gave the highest mineralisation of polyethylene plastic compared with other carriers. These findings are encouraging, but they come from controlled experiments rather than farmers' fields.

**5. Monitoring.** Detecting microplastics in soil is difficult, and there is no standard method. Studies mostly separate particles by density and flotation and then identify them under a microscope or with infrared spectroscopy, which makes results hard to compare between studies. Shared methods would help farmers and regulators judge how serious the problem is in a given field.

**Conclusion**

Microplastics enter agricultural soils through mulch films, sludge, compost, irrigation water, fertilisers and the air, and they build up because they degrade very slowly. They can weaken soil aggregates, change water behaviour, disturb soil organisms and alter plant growth, although the direction and size of the effects depend on the type of plastic and the soil. Because cleaning up contaminated land is slow and uncertain, the best approach is to stop plastics from entering in the first place through careful film use and recovery, better quality control of sludge and compost, and

supportive regulation. Earthworm-assisted degradation, plastic-degrading microbes and biochar are promising, but need field-scale testing. A combined approach of prevention, careful monitoring and further research will help protect soil health, crop production and food safety.

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# THE MACKEREL WAR - WHEN A FISH MOVED HOUSE AND NATIONS FELL OUT

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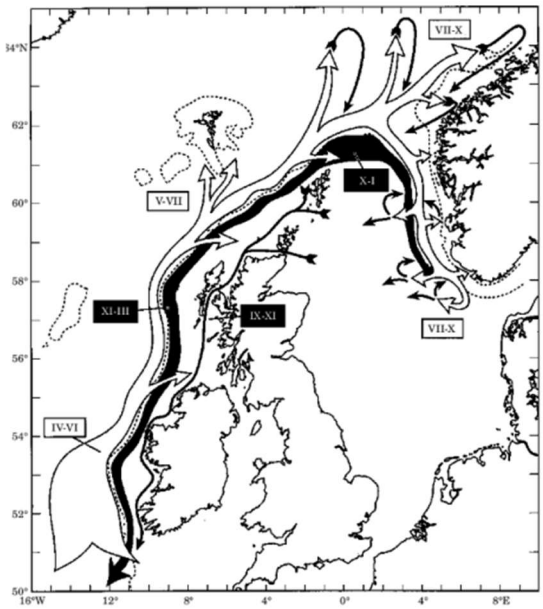
## A Fishery Dispute Without a Single Shot

The mackerel war is a long-running dispute between five governments bordering the Northeast Atlantic over how to share the catch of Atlantic mackerel. Although no weapons have been used, the disagreement has led to fishing boats being denied access to ports and trade sanctions being threatened or imposed. The conflict mainly concerns how much fish each country is allowed to catch. Fishing quotas and international agreements have become the main tools in this dispute. The issue is important because many fishing communities depend on mackerel for their livelihoods. The dispute is still ongoing, with the next round of negotiations scheduled for November–December 2026 (Karmactive, 2026).

## The Migration That Changed Everything

To understand why countries, disagree over mackerel, it is important to know about the fish's migration. Atlantic mackerel travel long distances in search of food. Every year, they lay their eggs in waters west of the British Isles. After spawning, the adult fish migrate north through the Norwegian Sea or west towards Iceland and Greenland to find plankton, their main food source (Astthorsson *et al*., 2012). For much of the twentieth century, mackerel mainly migrated through waters shared by the European Union (EU), Norway and the Faroe Islands. These countries were able to share the catch with relatively few disagreements. Iceland was not included in these discussions until December 2009 (Oceana, 2010). However, ocean temperatures gradually began to rise, affecting the distribution of the fish. Although mackerel had occasionally been seen near Iceland as early as 1895, large numbers began appearing in Icelandic waters from 2007 onwards. Their distribution expanded approximately 400 miles westward and more than 100 miles northward (Astthorsson *et al*., 2012). Scientists suggest that warmer ocean temperatures, an increase in the mackerel population and changes in plankton distribution may have contributed to this shift. As a result, Iceland gained access to a much larger mackerel fishery, creating disagreements over how the catch should be shared among the countries.

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Map of the Northeast Atlantic European shelf detailing the main migration pathways of the western mackerel. The dark paths represent the migration to spawning grounds west of the British Isles, while the light arrows indicate the post-spawning return routes heading north.
Map Credit: *Reid et al., (1997)*

**When Quotas Triggered an International Row**

By the late 2000s, large numbers of mackerel had begun appearing in Icelandic waters. Iceland wanted to participate in the fishery and receive a fair share of the catch. However, the other coastal countries did not agree to give Iceland the share it wanted. In response, Iceland increased its annual mackerel fishing quota from just 2,000 tonnes to 130,000 tonnes in 2010. The Faroe Islands soon followed by increasing its own fishing quota threefold (France 24/AFP, 2010).

These decisions led to disagreements with other countries. Norway restricted Icelandic and Faroese fishing vessels from using its ports, and some Scottish ports took similar action (British Sea Fishing, n.d.). In one incident, a Faroese fishing vessel was refused permission to land its catch at Peterhead, a major fishing harbour in Scotland. Scottish fishermen and politicians argued that Iceland and the Faroe Islands were taking more than their fair share of a resource shared by several countries (The Press and Journal, 2017). In 2012, the European Parliament supported trade sanctions against Iceland and the Faroe Islands, including a proposed ban on mackerel imports from both countries (LSE, 2012).

Iceland and the Faroe Islands believed that the existing system was outdated and needed to change. They wanted a fairer share of the mackerel catch because large numbers of fish were now found in their waters. In contrast, the EU and Norway argued that these two smaller nations were catching too much of a resource shared by several countries. Both sides had reasons for their positions, and their disagreement over how to share the catch continued for many years.

**Fifteen Years of Fishing Beyond Scientific Advice**

The mackerel war is different from a simple disagreement over borders because an independent scientific organisation provides advice on how many fish can be caught sustainably. The International Council for the Exploration of the Sea (ICES) publishes annual recommendations on

the number of mackerel that can be caught without harming the fish population in the long term. However, since 2010, the coastal countries have repeatedly set fishing quotas higher than the scientific recommendations. Over a period of 15 years, their combined quotas exceeded the recommended limits by an average of 39 per cent (The Fishing Daily, 2025).

As a result, the mackerel population faced increasing pressure. In 2019, the Marine Stewardship Council (MSC) withdrew the sustainability certification for Northeast Atlantic mackerel. This certification indicates that a fishery meets recognised sustainability standards. The decision was made because the fish stock had fallen below a safe biological level, catches continued to exceed scientific advice, and the countries had failed to reach a lasting agreement on sharing the catch. Following this decision, supermarket chains such as Waitrose suspended their sourcing of Northeast Atlantic mackerel (Seafood Source, 2025).

**The 2026 Agreement: Progress, but not Enough**

In 2026, ICES issued a strong warning and recommended reducing mackerel catches by 77 per cent, to just 174,357 tonnes. This major reduction was considered necessary to help the declining fish population recover. The recommendation caused concern in the fishing industry, with some industry representatives describing it as a “hammer blow” (The Fishing Daily, 2025; Seafood Source, 2025b).

In response, four coastal states the UK, Norway, the Faroe Islands and Iceland reached an agreement to reduce their combined mackerel catch by 48 per cent compared with 2025. They set the total allowable catch for 2026 at 299,010 tonnes (SeafoodSource, 2025a). This was the largest joint reduction these countries had agreed to. Conservation groups welcomed the move towards reducing fishing pressure. However, the agreed quota was still much higher than the 174,357 tonnes recommended by ICES. The EU and Greenland were not part of this agreement and continued to set their own fishing allocations. As a result, the total catch for 2026 was estimated at around 398,000 tonnes more than twice the level recommended by scientists (The Grocer, 2025).

“Urgent action to align all states with scientific recommendations is essential if we are to prevent further depletion and secure a sustainable future for northeast Atlantic mackerel.” - Brooke Schlipf, Marine Conservation Society, 2025

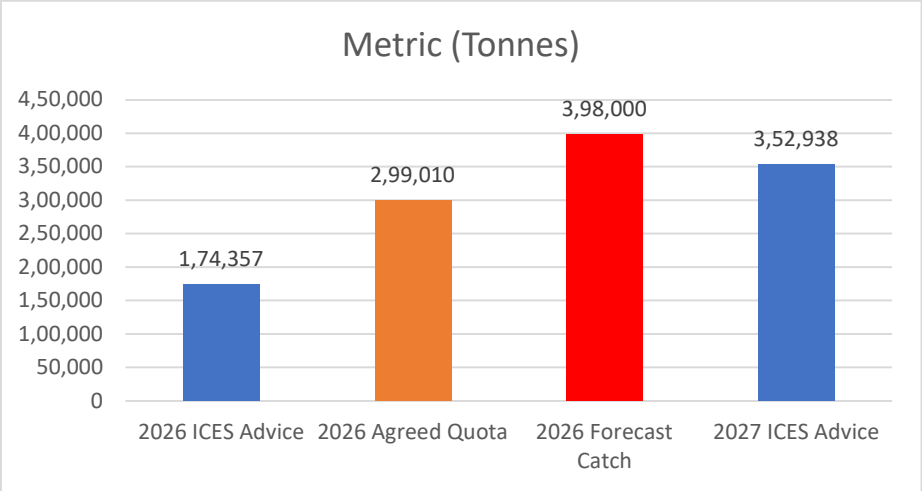
**An Unexpected Turn in the Stock's Recovery**

In late September 2026, the situation took an unexpected turn when ICES published its advice for 2027. Instead of recommending another major reduction, it more than doubled the recommended catch to 352,938 tonnes. According to ICES, the mackerel spawning stock had risen slightly above the critical biological limit. This offered some hope that the fish population was beginning to recover after years of overfishing (IntraFish, 2026).

However, scientists warned that the improvement should be treated with caution. The mackerel population had not yet fully recovered, and catches had continued to remain roughly twice as high as the scientific recommendations. NAPA, an industry organisation, used this development to call for a legally binding agreement involving all seven coastal states. It argued that the early signs of recovery showed the importance of cooperation, rather than providing a reason to increase fishing without proper controls (The Fishing Daily, 2026b).

The coastal states are scheduled to meet in November and December 2026 to negotiate the final fishing quota for 2027 (Karmactive, 2026). Although the scientific advice provides a basis for these

discussions, the final quota will depend on whether the countries can agree on how to share the catch. The outcome will be important for both the fishing industry and the long-term recovery of the Northeast Atlantic mackerel population.




An original bar chart comparing four figures: the 2026 ICES advice (174,357 t), the agreed 2026 quota (299,010 t), the forecast actual 2026 catch (about 398,000 t), and the 2027 advice (352,938 t). This single chart tells the whole story of the gap between science and politics at a glance. Credit: Chart based on ICES data.

**Why The Mackerel Dispute Matters Beyond the Atlantic**

The mackerel war may seem like a distant dispute between countries in the North Atlantic, but it highlights a much bigger problem. As the oceans become warmer, fish are moving into new areas faster than countries can update the rules used to manage them. This creates challenges in deciding which countries should have the right to catch these fish and how the catch should be shared fairly. The main lesson is not just about mackerel, but about whether international agreements and institutions can adapt as quickly as nature changes. For now, the fish continue to follow warmer waters, while countries remain caught up in disagreements over boundaries and fishing rights.

**The Mackerel War at a Glance**

| | |
|---|---|
| **Species** | *Scomber scombrus* (Atlantic mackerel) |
| **Dispute began** | 2010 - Iceland and the Faroe Islands set unilateral quotas |
| **Main parties** | UK, EU, Norway, Faroe Islands, Iceland, Greenland |
| **Cause** | Mackerel shifted north and west into Icelandic waters as seas warmed |
| **MSC sustainability certification** | Suspended in 2019 |
| **2026 ICES advice** | 174,357 tonnes |
| **2026 agreed quota (4 parties)** | 299,010 tonnes |
| **2026 forecast actual catch** | ≈398,000 tonnes |
| **2027 ICES advice** | 352,938 tonnes |
| **Next negotiation** | November - December 2026 |

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# *Thrips parvispinus* IN INDIAN CHILLI: FIVE YEARS OF INVASION, PAN-INDIA SPREAD AND INTEGRATED MANAGEMENT (2021–2026)

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**Abstract**

The South-East Asian thrips, *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae), has become an important invasive pest of chilli and capsicum in India. Although the species was recorded in India before 2021, damaging outbreaks in chilli were first widely documented in southern production regions during 2021. Since then, research surveys and molecular confirmations have demonstrated expansion into central, northern, eastern, and north-eastern parts of the country. This review synthesizes published evidence available up to 2026 on the pest's status, distribution, damage, biology, and management. Particular emphasis is given to northern India, where confirmed infestations have occurred in protected capsicum in Haryana and chilli fields in Uttar Pradesh. Evidence also supports its occurrence in Madhya Pradesh, Chhattisgarh, West Bengal, and other regions. The pest's polyphagy, flower preference, rapid colonisation of new areas, and potential displacement of resident thrips species complicate management. An integrated pest-management approach based on surveillance, accurate identification, cultural tactics, biopesticides, host-plant resistance, and selective insecticides is recommended.

**Keywords:** invasive thrips, chilli, capsicum, North India, pest surveillance, biological control, integrated pest management

## Introduction

Chilli (*Capsicum annuum* L.) is an important spice, vegetable, and commercial crop in India. Its productivity and fruit quality are often reduced by sucking pests, including thrips, mites, whiteflies, and aphids. Thrips are especially difficult to manage because they are small, cryptic, reproduce rapidly, and commonly inhabit protected plant parts such as terminal buds and flowers. Their feeding causes leaf distortion, flower injury, poor fruit set, and fruit scarring.

The invasive South-East Asian thrips, *Thrips parvispinus*, has altered the chilli pest complex in India. The species is native to South-East Asia and had been detected in India on papaya and ornamental hosts before it became a major chilli pest. Severe chilli outbreaks were documented from 2021 onwards, especially in Andhra Pradesh, Karnataka, and Telangana. Early investigations reported high infestation levels and severe crop losses in affected production areas (Prasannakumar *et al.,* 2021; Sridhar *et al.,* 2021).

The concern surrounding *T. parvispinus* is not merely its presence in chilli fields. It is a polyphagous pest that can use several cultivated plants, ornamentals, and alternate hosts. This feature permits persistence between cropping seasons and supports movement through mixed-farming landscapes. Molecular and field-survey work in Tamil Nadu identified the insect on chilli, capsicum, and 15

associated crops, demonstrating its capacity for host expansion in Indian agroecosystems (Palanisamy *et al.,* 2023).

The year 2026 is therefore an appropriate point to assess the pest as an established and expanding invasive threat rather than as a newly detected outbreak. Available records show that *T. parvispinus* has spread beyond its initial southern focus. However, pest status should be interpreted carefully: a confirmed record in a state does not automatically indicate uniform distribution across that entire state. Continued district-level surveillance and molecular confirmation remain essential.

**Pest status and taxonomic importance**

*Thrips parvispinus* belongs to the order Thysanoptera and family Thripidae. It is often called black flower thrips because adults are dark coloured and frequently occur in flowers. Correct species diagnosis is essential because chilli and capsicum may contain a complex of thrips species, including *Scirtothrips dorsalis*, *Thrips palmi*, *Thrips tabaci*, and *Frankliniella schultzei*.

Misidentification can lead to ineffective management. Morphological identification using taxonomic characters should be supported, where feasible, by DNA barcoding or molecular markers. Hulagappa *et al.* (2022) used both morphological and molecular approaches to confirm the invasive species and assess its potential distribution under present and future climatic conditions. Similarly, Palanisamy *et al.* (2023) used species-specific characters and mitochondrial COI analysis to study its occurrence and genetic composition in Tamil Nadu.

The ability of *T. parvispinus* to become dominant in chilli is especially important. Surveys in southern India found that it dominated the thrips assemblage in several chilli fields, where the historically common *S. dorsalis* was absent or represented only minimally. This observation suggests potential competitive displacement, although repeated long-term studies are needed to determine whether such displacement is permanent, seasonal, or location-specific (Sridhar *et al.,* 2021).

**Pan-India pest status, 2021–2026**

The spread of *T. parvispinus* in India has been documented through surveys, pest reports, and molecular confirmations. The strongest published evidence is available for individual districts and production belts rather than for every state.

| Region | Published evidence of occurrence | Interpretation |
|---|---|---|
| South India | Andhra Pradesh, Karnataka, Telangana, Tamil Nadu, and Kerala | Initial major chilli outbreaks and continuing establishment |
| West and central India | Gujarat, Maharashtra, Madhya Pradesh, and Chhattisgarh | Confirmed expansion through field surveys and reports |
| North India | Haryana and Uttar Pradesh | Confirmed in protected capsicum and open-field chilli |
| East and north-east India | West Bengal | Molecularly confirmed in chilli in Alipurduar District |
| National status | Present and widespread | Regional intensity and crop impact still require regular validation |

Southern India remains the best-documented epicentre of economically damaging chilli infestations. Surveys in Karnataka during 2021 identified *T. parvispinus* as the predominant species in major chilli-growing districts (Prasannakumar *et al.,* 2021). In Andhra Pradesh, Karnataka, and

Telangana, the species was observed to dominate chilli-thrips communities, and reports indicated major damage during the outbreak period (Sridhar *et al.,* 2021). In western India, *T. parvispinus* was reported in chilli fields in Gujarat, including the Anand district. Patel *et al.* (2022) recorded infestation in several talukas, confirming that the pest had expanded far beyond the original southern outbreak area. Research from Tamil Nadu provides further evidence of rapid adaptation. Palanisamy *et al.* (2023) found that the insect expanded rapidly in north-western, western, and Cauvery Delta regions of the state. The study also demonstrated co-occurrence with other thrips on chilli and capsicum, showing that the invasive species can become part of complex multi-species pest communities.

**Status in Northern India**

Northern India deserves particular attention because chilli and capsicum are grown in both open fields and protected structures, and the invasive pest has already been confirmed in several locations.

**Haryana**

A study on the spread of *T. parvispinus* in north India recorded infestations on capsicum hybrids grown under protected cultivation in Ambala, Panipat, and Panchkula districts of Haryana. The highest reported infestation was in Ambala, reaching up to 16 thrips per flower. Affected capsicum plants showed flower browning, leaf yellowing, stunting, and deformed fruits (Hulagappa *et al.,* 2023**)**. This finding is important because protected cultivation can provide favourable conditions for rapid pest multiplication. Dense plant canopy, continuous crop availability, and limited natural-enemy activity may permit populations to build quickly. Nursery and protected-cultivation systems should therefore be treated as priority sites for monitoring and sanitation.

**Uttar Pradesh**

Molecularly confirmed chilli infestations have been reported from Varanasi and Mirzapur districts of Uttar Pradesh. Sethy *et al.* (2023) recorded mean populations of 9.1 and 9.3 thrips per three leaves in Varanasi and Mirzapur, respectively. Flower populations averaged 3.1 and 5.1 thrips per flower. The study established that *T. parvispinus* had attained pest status in eastern Uttar Pradesh. A subsequent population-dynamics study in Prayagraj, Uttar Pradesh, also indicated continued research attention to the pest in the region. Together, these findings demonstrate that the species is not confined to southern India and has become relevant to northern chilli production.

**Central Indian corridor**

Field surveys associated with the north-India spread study also recorded infestations in Madhya Pradesh and Chhattisgarh. In Madhya Pradesh, chilli fields in Khargone, Khandwa, Satna, Narsinghpur, and Dhar were surveyed. In Chhattisgarh, infestations were reported from districts including Bastar, Sarangarh-Bilaigarh, and Balod Bazar **(**Hulagappa *et al.,* 2023). These central Indian records are epidemiologically important because they suggest a geographic corridor linking the initial southern outbreak zone with northern and eastern production areas.

**West Bengal and north-eastern relevance**

In 2024, *T. parvispinus* was molecularly confirmed from chilli in Alipurduar district, West Bengal. Subsequent surveys found the pest in nearby villages, demonstrating local spread after detection (Chatterjee *et al.,* 2024). This record expands concern toward the north-eastern and eastern chilli-growing landscape.

**Damage symptoms and economic significance**

Both adults and immature stages feed by rasping plant tissues and withdrawing cell contents. The pest is frequently concentrated in flowers, flower buds, terminal leaves, and young fruits.

Characteristic damage symptoms include:

- Silvery patches or bronzing on tender leaves.
- Curling, distortion, and reduced expansion of young leaves.
- Injury to terminal buds, resulting in compact or stunted growth.
- Browning and shedding of flower buds and flowers.
- Reduced fruit set.
- Scraping, scarring, discolouration, and deformation of young fruits.
- Lower market value of fresh and dry chilli because of poor visual quality.

The pest's preference for flowers makes it particularly destructive. While leaf injury reduces photosynthetic area, flower injury reduces reproductive success directly by causing flower drop and poor fruit formation. Current field research in Telangana found the pest from vegetative growth through harvest, with higher infestation in flowers than fruits (Srinivasnaik *et al.,* 2025). Reported yield-loss estimates during initial outbreaks were high, but they should not be treated as universal. Damage depends on crop stage, cultivar, weather, local pest pressure, plant nutrition, insecticide history, and management timing.

**Biology and invasive potential**

The biological characteristics of *T. parvispinus* support rapid population increase under favourable conditions. Laboratory work on chilli at 25 ± 1°C reported a mean egg incubation period of 5.74 days, total larval duration of 5.92 days, pre-pupal duration of 1.83 days, and pupal duration of 4.17 days. Females lived longer than males and produced a mean of approximately 15.5 eggs per female (Priyanka *et al.,* 2024).

Its invasion success is associated with:

1. A broad host ranges.
2. Capacity to exploit flowers and young tissues.
3. Rapid development under favourable temperature conditions.
4. Adaptation to both open-field and protected cultivation.
5. Movement through plant material and horticultural trade.
6. Potential reduction in control effectiveness when insecticides are overused.

Climate-risk modelling indicates that major chilli- and papaya-growing regions, together with favourable climatic conditions, may support further establishment and spread in India (Hulagappa *et al.,* 2022).

**Integrated pest management**

Management must be preventive and integrated. Repeated insecticide sprays alone are unlikely to provide durable control and may disrupt natural enemies, create residues, and select resistant populations.

**Surveillance and identification**

Fields should be inspected from the nursery stage onwards. Sampling should focus on terminal shoots, young leaves, flower buds, and flowers. Blue sticky traps may be used to monitor adult activity, but direct plant examination is necessary because flower-dwelling populations may not be fully represented in trap catches.

**Cultural management**

Important cultural measures include synchronized planting within a locality, removal of heavily infested crop residues, weed management, sanitation around protected structures, and avoidance of continuous crop availability. Nurseries should be regularly inspected because infested seedlings can spread the pest to new fields.

**Biological and botanical management**

Microbial biopesticides are promising components of IPM. ICAR–NBAIR has identified fungal and bacterial candidates, including *Beauveria bassiana*, *Lecanicillium fusisporum*, *Bacillus albus*, and *Pseudomonas fluorescens*, for managing thrips in chilli. Their field performance depends on formulation, spray coverage, humidity, timing, and repeated application. Botanical and biorational products may also have a role in early pest suppression. Jeyashree and Arivudainambi (2025) found several biorational treatments effective under semi-field conditions. Such products should be used as components of an IPM module, not as isolated substitutes for surveillance and crop sanitation.

**Host-plant resistance**

Host-plant resistance is among the most sustainable long-term approaches. Screening of 481 chilli germplasm accessions identified several resistant accessions, including IIHR-B-HP-79, as potential sources for breeding programmes (Kumar *et al.,* 2024). Resistant cultivars should be combined with IPM because resistance may be partial and can vary among pest populations and environments.

**Selective chemical management**

If economic damage is imminent, approved insecticides may be applied according to current local recommendations. Applications should be need-based, directed towards terminal growth and flowers, and rotated across insecticide modes of action. The same insecticide group should not be used repeatedly. Farmers should follow only labels and advisories approved for the crop and region.

**Conclusion**

From 2021 to 2026, *Thrips parvispinus* has progressed from an emerging chilli pest in southern India to a widespread invasive threat with confirmed records in central, northern, eastern, and north-eastern regions. Northern India is no longer a hypothetical risk area: published evidence confirms infestations in Haryana and Uttar Pradesh, while central Indian records indicate an important pathway of spread. The most effective response is surveillance-led IPM. Accurate identification, clean planting material, sanitation, cultural practices, biological control, resistant cultivars, and selective rotation-based insecticide use should be integrated at farm and community levels. Continued research is essential to prevent further spread and protect chilli and capsicum production across India.

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# PROXIMAL SENSORS FOR SOIL HEALTH MONITORING: ADVANCES, CONSTRAINTS, AND FUTURE DIRECTIONS

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## Introduction

Healthy soil is the foundation of productive, sustainable agriculture. It supports plant growth, stores and supplies water, provides nutrients, and sustains organisms that help maintain soil function. However, soil health cannot be judged by crop appearance alone. Farmers and advisers need information about soil properties and how they vary across a field. Traditional soil testing remains essential because it provides reliable measurements of important soil properties. However, collecting samples across a large field and sending them for laboratory analysis can be time-consuming and costly. A small number of samples may also miss important differences within a field. Proximal soil sensing offers an additional way to collect soil information quickly and in greater spatial detail.

## What are proximal soil sensors?

Proximal soil sensors are instruments used on, in, or close to the soil. They may be handheld, pushed into the ground, mounted on farm machinery, or installed at fixed monitoring points. Different sensors measure different signals, including reflected light, electrical properties, elemental composition, moisture-related responses, and selected chemical conditions.

When measurements are linked to GPS locations, they can reveal where soil conditions vary within a field. This information can help identify areas that need further sampling and support decisions about irrigation, nutrient management, and soil conservation. Sensors do not all measure the same properties, and some provide indirect estimates rather than direct measurements. Their results should therefore be interpreted in light of each sensor's purpose and checked against suitable reference tests.

## Why does this matter?

A field may contain wetter and drier patches, areas with different salinity levels, or zones with contrasting soil textures. Managing every part of the field in exactly the same way may not always be efficient. Sensor-based information can help reveal these differences, provided the measurements are reliable and inform practical management decisions.

## Major types of proximal soil sensors

### Spectroscopy sensors

Spectroscopy sensors direct light onto soil and measure the light that is reflected or absorbed. Visible–near-infrared (Vis–NIR) and mid-infrared spectroscopy can be used to estimate selected soil properties, including soil organic carbon, organic matter, texture, and some mineral characteristics. These methods are useful because a single spectral reading can contain information related to several soil properties.

However, a spectrum does not automatically provide an accurate soil test result. Predictions depend on calibration using soil samples whose properties have already been measured. Soil moisture, mineralogy, sample preparation, and differences between instruments can all affect the results. Spectroscopy is therefore best treated as a rapid estimation tool supported by laboratory reference data.

**Electrical and electromagnetic sensors**

Electrical conductivity sensors and electromagnetic induction instruments help identify variation in soil conditions. Their readings may be influenced by moisture, salinity, clay content, temperature, and other factors. These sensors are often useful for mapping patterns and identifying areas that warrant closer inspection, but a reading alone may not reveal what caused the variation.

Soil moisture sensors, such as time-domain reflectometry and frequency-domain reflectometry instruments, estimate water content from the soil's electrical or dielectric response. They can support irrigation scheduling and the monitoring of changes in soil water. Correct installation, appropriate calibration, and an understanding of soil type and salinity are important for obtaining useful readings.

**Portable X-ray fluorescence (pXRF)**

Portable X-ray fluorescence instruments provide rapid information about the elemental composition of soil. Depending on the instrument and measurement conditions, they can help screen for elements such as iron, calcium, copper, zinc, and selected potentially harmful elements. This can be useful for soil surveys and preliminary contamination screening.

It is important to distinguish total elemental measurements from measurements of nutrients that plants can actually take up. Routine pXRF instruments cannot reliably measure nitrogen directly. Phosphorus and potassium may be detected as elements, and research is exploring ways to estimate plant-available forms from calibrated data. These estimates are indirect and depend on soil conditions, so standard tests for available nutrients remain important.

**Electronic and electrochemical sensors**

Electronic and electrochemical sensors can measure soil pH and, depending on their design, selected ions such as nitrate, ammonium, or potassium. They can provide rapid, portable measurements and may connect to handheld devices or monitoring systems. Their accuracy can be affected by interference from other ions, sensor drift, fouling, and differences in soil conditions. Calibration and regular checks are therefore necessary before readings are used to guide nutrient decisions.

**Sensors and indicators for biological activity**

Soil biological health is more difficult to assess than moisture or pH because soil contains many organisms that perform different functions. Soil $CO_2$ efflux—the release of carbon dioxide from the soil surface—is often used as an indicator or proxy for soil respiration. It reflects both root and microbial activity and is influenced by temperature, moisture, and the availability of material for decomposition.

Field $CO_2$ monitoring and emerging biosensors may provide useful information about selected biological processes. However, $CO_2$ efflux is not a direct measure of microbial biomass or diversity. Laboratory and molecular methods remain important when reliable estimates of microbial biomass,

enzyme activity, or community composition are needed. Biological indicators should be selected to address the specific question at hand, rather than relying on a single sensor to describe all aspects of soil life.




***Figure 1: Popular Proximal Sensors and What They Measure***

**Connecting sensors with maps and computer models**

Sensor readings become more useful when combined with other sources of information. A practical workflow begins with GPS-linked field readings and soil samples. Selected samples are then analysed in a laboratory to provide reference measurements. Satellite images, terrain information, and other relevant data can also be incorporated using a geographic information system.

Computer models can use these combined datasets to estimate soil properties at locations where direct measurements are unavailable. The resulting digital soil maps may show patterns in soil organic carbon, salinity, moisture, or other indicators. These maps can help target additional sampling and support field management. However, combining datasets does not guarantee accurate results. Good sampling, appropriate calibration, independent validation, and clear reporting of uncertainty are essential.

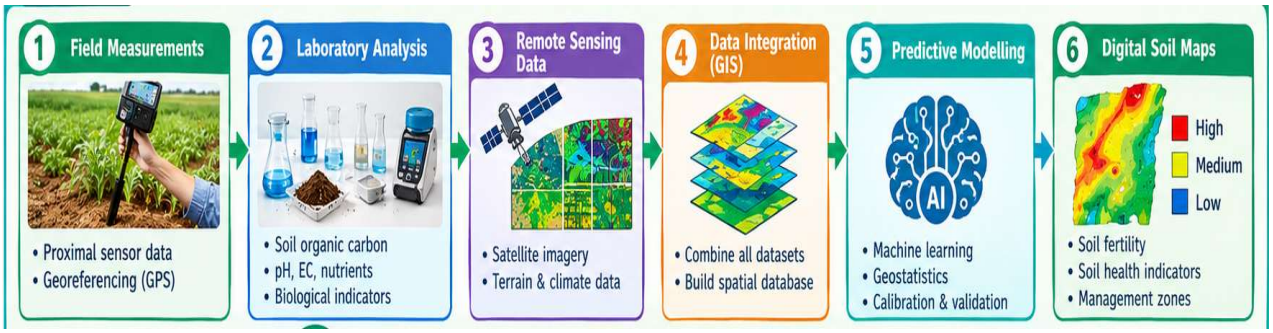



***Figure 2: A generalized workflow linking proximal sensor readings, laboratory reference data, and geospatial layers in a digital soil mapping process***

**Challenges and future opportunities**

**Calibration and local differences**

Soils vary across regions because of differences in parent material, texture, climate, management, and moisture. A sensor model developed for one location may not perform as well in another. Researchers are testing approaches such as local adaptation, transfer learning, and spectral libraries to make better use of existing calibration data. These methods may reduce the amount of new data required, but they do not eliminate the need to check performance using representative local samples.

**Cost, maintenance, and skills**

Some advanced instruments require a substantial initial investment. Maintenance, software, operator training, and laboratory testing also add to the cost. Sensors should be selected according to the problem they are intended to solve. A simpler, more affordable instrument may be more useful than an advanced system if it provides reliable information for a clear farm decision.

**Understanding what a sensor really measures**

A sensor measures a particular signal, which may not directly correspond to the final soil property of interest. Electrical conductivity, for example, can respond to several soil conditions. Spectroscopy often estimates properties using a calibration model, while $CO_2$ efflux indicates respiration rather than providing a complete measure of soil biology. Clear interpretation helps prevent misleading conclusions.

**Relevance to Indian agriculture**

India has diverse soils, climates, crops, and farming systems. An approach that works in one region may need to be adapted for another. As a practical recommendation—not a proven universal sequence—farmers and local advisers could begin with affordable measurements, such as soil moisture, pH, and electrical conductivity, when these address a specific management question. Routine laboratory soil testing should continue to provide essential reference information.

Agricultural universities, research institutions, and soil-testing laboratories can evaluate more advanced tools, including spectroscopy, electromagnetic sensing, and pXRF, for specific local applications. Field trials should compare sensor results with standard tests and assess both cost and practical value. Satellite imagery and GIS can then help extend validated field observations into maps while indicating where predictions are uncertain.

For smallholder farmers, adoption will depend on affordability, reliable local results, accessible technical support, and evidence that the information improves decisions. Training and extension services can help farmers understand both the benefits and the limitations of sensor-based information.

**Conclusion**

Proximal soil sensors offer a practical way to collect soil information quickly and reveal variation within agricultural fields. Spectroscopy can help estimate selected soil properties, electrical and electromagnetic sensors can map variation, pXRF can screen for many elements, and electronic sensors can measure selected chemical conditions. Biological indicators, including soil $CO_2$ efflux, can provide useful information, but they must be interpreted carefully.

These technologies are most valuable when used alongside laboratory testing, GPS, satellite information, GIS, and appropriate computer models. Their results depend on sound calibration, representative sampling, local validation, and an understanding of what each sensor actually measures. New approaches such as transfer learning and spectral libraries may improve the use of models across locations, but local checks remain necessary.

For Indian agriculture, the goal should not be to replace conventional soil testing or to adopt the most advanced instrument everywhere. Instead, sensor choices should match local needs, available resources, and clearly defined farm decisions. Used carefully, proximal sensing can help farmers and advisers obtain more detailed soil information and make better-informed decisions to support soil health and sustainable crop production.

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# NANO FERTILIZERS IN SOIL: EFFECTS ON NUTRIENT USE EFFICIENCY AND CROP PRODUCTIVITY

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**Abstract**

Crops use only part of the nitrogen, phosphorus and potassium applied as conventional fertiliser, and the rest is lost to air, water and soil. Nano fertilizers are nutrient carriers or particles of nanometre size, designed to release nutrients slowly or to deliver them directly to the plant, so that smaller doses can do the same job. This article explains how nano fertilizers work in soil and on the leaf, what field and pot studies report on nutrient use efficiency and yield, and what is known about their effects on soil. Reported benefits include similar yield at 75% of the recommended nitrogen dose in finger millet and rice, but results vary with crop, dose and location, and savings fall away when the dose is cut too far. Cost, regulation and the long-term fate of nanoparticles in soil remain open questions, so nano fertilizer are best seen as a supplement to good soil and nutrient management, not a replacement for it.

**Keywords:** Nano fertilizer, nano urea, nutrient use efficiency, soil health, crop productivity

## Introduction

Fertilisers have helped feed a growing population, but they are used inefficiently. When urea or other fertilisers are applied to soil, a large share never reaches the crop. For nitrogen, it has been estimated that up to 50–70% of what is applied can be lost through leaching, volatilisation or runoff (Saurabh *et al*., 2024). These losses waste money for the farmer and can pollute water and air. Nanotechnology offers one way to tackle this problem. Nano fertilizers use particles or carriers measured in nanometres, which have a very large surface area compared with their weight. Because of this, they can interact more closely with roots and leaves and can be built to release nutrients slowly. In India, liquid nano urea and nano zinc are already sold for foliar spraying, and a parliamentary committee has noted claims that a 500 ml bottle can replace a 45 kg bag of urea (Down To Earth). Figure 1 compares the idea behind the two approaches.

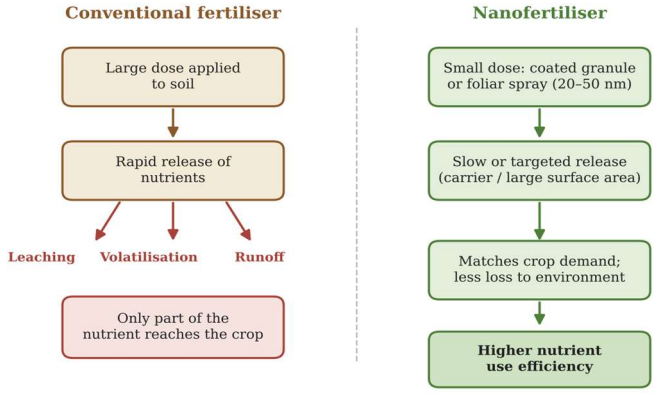



***Figure 1: Conceptual comparison of conventional fertiliser and nano fertilizer (schematic, not measured data)***

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**What are nano fertilizer?**

A nano fertlizer is a nutrient source in which the nutrient is either itself nanosized or is held on or inside a nanoscale carrier. Reviews describe several types: nutrient nanoparticles such as nano zinc, nano urea sprayed on leaves, nutrients held in chitosan or other biopolymer shells, nanoclay-polymer composites, and nano-biochar (Saurabh *et al*., 2024). The commercial nano urea and nano zinc used in field trials in India are in the range of 20–50 nm and are applied as foliar sprays (Sneha *et al*., 2025).

**How do they work?**

Reviews point to three main mechanisms. First, the large surface-to-volume ratio and high reactivity may improve contact with roots and leaves and so aid uptake. Second, in carrier-based products the nutrient is released gradually from a polymer, clay or chitosan matrix, which can match supply to crop demand and cut leaching and volatilisation. Third, some carriers release their nutrient in response to conditions such as pH, temperature or moisture. Nanoparticles can enter roots through the cell walls and cell interiors, and enter leaves through the cuticle and stomata, and are then moved through the plant's conducting tissues (Saurabh *et al*., 2024).

**What do the studies show?**

A 2024 review reports that nano fertilizer can raise nutrient use efficiency by up to 30% and crop yield by up to 20%, and may replace up to half of conventional fertiliser, although the review itself does not always tie these headline figures to specific studies (Saurabh *et al*., 2024). They should therefore be read as upper limits. Table 1 collects results from individual studies that give clearer numbers.

**Table 1: Selected results from field and pot studies with nanofertilizers**

| Study and crop | Treatment | Main result |
|---|---|---|
| Finger millet, Bengaluru (Sneha *et al*., 2025) | 75% of recommended N with foliar nano-N and nano-Zn | Grain yield of 3449 kg/ha, statistically equal to 3453 kg/ha at the full N dose |
| Rice, Varanasi and Guwahati (CGIAR study) | Urea at 66–75% of recommended N plus two nano-urea sprays | Matched full-dose yield; saved 27–40 kg N/ha (Varanasi) and 15–20 kg N/ha (Guwahati) |
| Rice, same study | Urea at 50% of recommended N plus nano-urea | Yield fell by about 16–19%, so nano-urea did not make up for a large cut |
| Maize pot trial, chitosan-based K nano fertilizer (Saurabh *et al*., 2024) | 75% of the standard K rate versus 100% KCl | Fresh and dry biomass higher by 51% and 47% |

The finger millet and rice studies are the most useful for farmers because they used field conditions and tested different nitrogen levels. In finger millet, 75% of the recommended nitrogen with nano-nitrogen and nano-zinc sprays gave almost the same grain yield as the full dose, and more than double the yield of the control that received only phosphorus and potassium (Sneha *et al*., 2025).

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Under this treatment, apparent recovery of applied nitrogen was about 61%, compared with about 41% for potassium and about 15% for phosphorus (Figure 2).

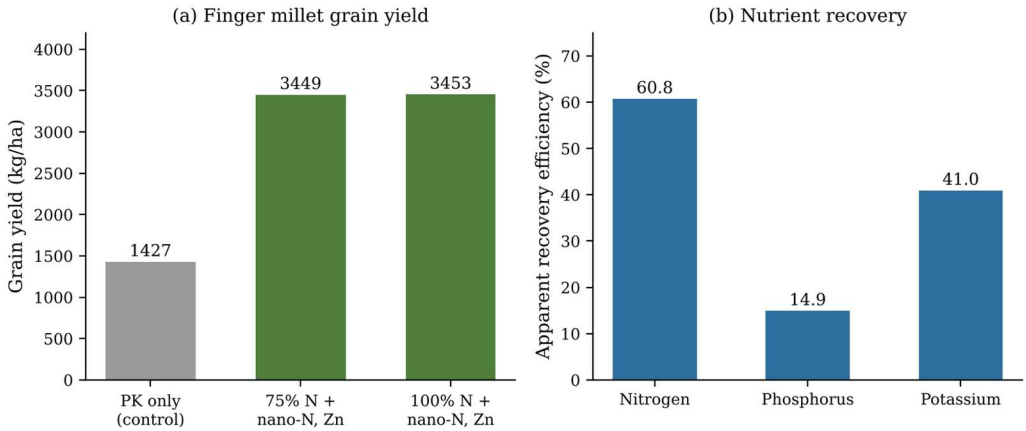



***Figure 2: (a) Grain yield of finger millet and (b) apparent recovery efficiency of nutrients under 75% of the recommended nitrogen plus foliar nano-N and nano-Zn. Data from Sneha et al., (2025), pooled over two seasons***

The rice trials show the limits. Two nano-urea sprays together with 66–75% of the recommended urea matched the full-dose yield and gave comparable returns, but cutting urea to half the recommended dose reduced yield by about 16–19% even with nano-urea added (CGIAR study). Nano fertilizer can therefore trim nitrogen use moderately, but they do not make up for a large reduction.

Not every result is as positive. A parliamentary committee noted that top dress nitrogen savings in field trials varied from 25 to 50% between crops and regions, and recommended audits of the trials to explain the variation and to develop crop-specific application methods (Down To Earth).

**Effects on soil**

Most of the evidence on nano fertilizer concerns crops rather than soil, but some results point to benefits. In the finger millet study, available nitrogen, phosphorus and potassium in soil were lowest under the full nitrogen dose, while the 75% dose with nano sprays left more nitrogen, phosphorus and potassium in the soil, and nitrogen losses were highest under the full dose (Sneha *et al*., 2025). Slow-release carriers may also reduce losses. For example, nanoclay-polymer composites inhibited nitrification by 30–87% and lowered nitrous oxide emissions by 16.1% in rice and 12.4% in wheat compared with urea, and nano-biochar reduced runoff on sloping farmland by about 11–32% (Saurabh *et al*., 2024).

At the same time, the long-term effects on soil are poorly known. The authors of the finger millet study point out that accumulation of nanoparticles, microbial diversity and wider ecological impacts remain understudied (Sneha *et al*., 2025), and reviews warn that nanoparticles may persist in soil, move to groundwater or build up in crops (Saurabh *et al*., 2024).

**Challenges**

Several issues must be settled before nano fertilizer can be recommended widely. Evidence is still short term, and the parliamentary committee noted that studies on crop nutritional quality mostly ran for only one year and one season (Down To Earth). High concentrations of metal-based

nanoparticles can cause oxidative stress, leaf burn and reduced photosynthesis in plants, so dose matters (Saurabh *et al*., 2024). Costs, regulation and labelling are still developing, and performance may differ with soil texture, pH and climate (Sneha *et al*., 2025). Farm workers may also be exposed during spraying, and exposure through food needs to be assessed (Saurabh *et al*., 2024).

**Practical outlook**

For now, the most sensible use of nano fertilizer is as a supplement within an integrated plan. Based on the studies above, foliar nano sprays combined with a moderately reduced soil dose of about 75% of the recommendation have matched full-dose yield in finger millet and rice, but deeper cuts have not. Farmers should follow crop-specific recommendations, avoid over-application, and continue to base nutrient plans on soil testing. Long-term trials across soil types and seasons, together with safety assessment, will decide how large a role nano fertilizer can play.

**Conclusion**

Nano fertilizer aim to deliver nutrients in smaller amounts and in step with crop demand, and so improve nutrient use efficiency and reduce losses to the environment. Field studies in finger millet and rice show that about three-quarters of the recommended nitrogen with nano sprays can give yields equal to the full dose, but results vary between crops and places, and large dose reductions lose yield. Information on their long-term behaviour in soil, effects on soil organisms, cost and safety is still limited. Used carefully as a supplement and backed by soil testing and further research, nano fertilizer may help farmers produce more with less fertiliser.

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# WALRUSES: MASTER OF LIFE IN THE ARCTIC

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## Introduction

In the frozen wilderness of the Arctic, where icy seas stretch to the horizon, one remarkable marine mammal stands out the walrus. With its massive body, long ivory tusks, thick whiskers and wrinkled skin, the walrus is one of the most recognizable animals of the polar world. Its scientific name is *Odobenus rosmarus*, and it belongs to the family Odobenidae (Lowry, 2026). Walruses are perfectly adapted to survive in extreme Arctic conditions. A thick layer of blubber protects them from freezing temperatures, while their powerful flippers help them swim efficiently through icy waters. Their sensitive whiskers, known as vibrissae, help them locate clams, mussels, worms and other organisms hidden beneath the seafloor (Fay, 1982). Their most striking feature is their pair of long tusks, which are actually elongated canine teeth. Both males and females possess tusks, which are used for defence, social interactions and climbing onto ice. Walruses are also highly social animals and often gather in large herds on sea ice or coastal areas. Today, the walrus faces growing challenges from climate change and declining sea ice (Kovacs *et al*., 2011). As a symbol of the Arctic ecosystem, its survival is closely connected to the health of the polar environment. Understanding the walrus helps us appreciate the extraordinary adaptations and fragile balance of Arctic life.

**Taxonomical Classification**

| Rank | Classification |
|---|---|
| Kingdom | Animalia |
| Phyllum | Chordata |
| Class | Mammalia |
| Order | Carnivora |
| Family | Odobenidae |
| Genus | Odobenus |
| Species | *Odobenus rosmarus* (Lowry 2016) |



*Odobenus rosmarus*

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**Distribution**

The walrus (*Odobenus rosmarus*) is mainly distributed in the Arctic and subarctic regions of the Northern Hemisphere (Fay, 1982). It is commonly associated with the ice front and northern seas, but its distribution is not restricted to the ice edge. Some walruses may occur about 1,000 miles south of the ice front in summer and about 500 miles north of it in winter. They mainly inhabit the shallow waters of the continental shelf, where they feed on molluscs and other benthic invertebrates (Fay, 1982), generally at depths of 80 m or less. Their year-round distribution includes parts of both the Arctic and Boreal (subarctic) zones. The Pacific walrus population is concentrated around the Bering Sea and Bering Strait (Alaska Department of Fish and Game, n.d), with St. Lawrence Island forming an important area. Round Island in Bristol Bay, Alaska, represents the southernmost area regularly occupied by Pacific walruses during summer.




**Distinctive Characteristics**

Walruses are very large and bulky marine mammals with several distinctive features. Their tail is attached to the body by a web of skin, while the muzzle is very short, broad and flat-ended. Unlike seals, walruses have no external ear pinnae. Their most remarkable feature is the presence of two massive upper canine teeth, which are enlarged into long tusks (Fay, 1982). In adults, these tusks may extend up to 1 metre outside the mouth, except when they are worn or broken. In males, the tusks are generally less curved and more divergent at the tips. Most walruses have a characteristic greyish cinnamon-brown colour. With males measuring 2.7-3.6 m and weighing 800-1,900 kg, while females measure 2.3-3.0 m and weigh 400-1,200 kg (Fay, 1982).

**Behaviour**

Walruses are highly social marine mammals that are often seen in large groups or herds, both in water and on land. They spend much of their time swimming and feeding in the cold Arctic waters. Walruses prefer to haul out and rest on snow-covered, moving pack ice, although they may also gather on small rocky islands or mainland shores when sea ice is unavailable. Their habitat is closely associated with shallow coastal waters, where they search for food on the ocean floor, generally at depths of less than 100 m. They particularly prefer areas with a gravelly or suitable bottom, which support their preferred benthic prey. Walruses spend considerable time diving and searching the seafloor for food using their sensitive whiskers, known as vibrissae (Fay, 1982). Their long tusks have several important functions. They help walruses pull themselves out of the water onto ice or land and are also used during social interactions and displays. Contrary to popular belief, tusks are not primarily used for digging food from the seabed.

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Walruses are generally peaceful and strongly social, with individuals often resting close together. Herds may contain many animals, and their social behaviour includes vocalizations, physical contact and interactions between individuals. Mothers also remain closely associated with their young, providing protection and care.




**Fig. 418** *Odobenus rosmarus*

**Food and Feeding**

Walruses are mainly benthic feeders, obtaining most of their food from the ocean floor. Their diet consists mainly of molluscs, particularly clams and mussels, along with other bottom-dwelling invertebrates such as worms, snails, shrimps and crabs (Fay, 1982). They generally feed in shallow coastal waters, usually at depths of less than 100 m, where benthic prey is abundant. Walruses locate their prey using their highly sensitive moustache-like whiskers (vibrissae), which help them detect organisms hidden in the sediment. They use their strong lips and mouth to collect and extract prey from the seabed. Walruses can also create water currents with their mouths to expose buried prey. Their powerful jaws help them process hard-shelled molluscs. Feeding usually involves repeated dives to the seafloor, followed by returning to the surface to breathe. Their feeding grounds are often associated with soft or gravelly bottom habitats that support rich benthic communities.

**Life Cycle**

The reproductive cycle of the walrus begins with the breeding season, which generally occurs from December to March during the harsh Arctic winter (Fay, 1982). Breeding takes place mainly on pack ice, where males produce characteristic sounds and vocalizations to attract females. Walruses are believed to be polygynous, meaning that a male may mate with more than one female. During the breeding season, males may establish small aquatic territories close to females that are hauled out on ice floes. Males actively defend these areas and use loud vocalizations, body displays and other courtship behaviours to attract females. These displays are an important part of the mating process.

Competition between males can be intense. Male-male fighting occurs as individuals compete for access to females. Larger and stronger males may have an advantage during these interactions. The combination of vocalization, territorial behaviour and physical displays helps males establish their position during the breeding period.

After successful mating, the female carries the developing embryo through a period that includes delayed implantation (Roth, 1990), an adaptation that allows reproduction to be synchronized with favourable seasonal conditions. The female eventually gives birth to a single calf, usually on sea ice or land. The young walrus remains closely associated with its mother and depends on her milk for nourishment during its early development. As the calf grows, it gradually becomes more independent and learns important behaviours such as swimming, diving and feeding. Young walruses remain socially associated with other members of the herd. With growth and maturation,

they eventually become adults and participate in the reproductive cycle, continuing the life cycle of the species.

**Exploitation and Threats**

Walruses have historically been subjected to human exploitation, mainly for their meat, blubber, hide, tusks and bones (Fay, 1982). Commercial hunting during earlier periods caused substantial pressure on walrus populations, while subsistence harvesting continues to be important for some Arctic communities. Sustainable management and monitoring are therefore essential for maintaining population stability. Walruses are also exposed to natural predation. Adult and juvenile walruses may be preyed upon by polar bears (*Ursus maritimus*) and killer whales (*Orcinus orca*), while calves are particularly vulnerable. However, predation is generally considered a natural ecological factor rather than the principal threat to present-day walrus populations. Among contemporary threats, climate change is of major concern (Kovacs *et al*., 2011). Declining Arctic sea ice can reduce suitable haul-out platforms and alter the availability and distribution of benthic feeding habitats. Changes in oceanographic conditions may consequently affect feeding behaviour, energetic expenditure and population distribution. The walrus is particularly dependent on shallow continental-shelf ecosystems, where it obtains molluscs and other benthic invertebrates. Additional anthropogenic pressures include increasing Arctic shipping, underwater noise, industrial development, tourism, pollution and oil-spill risks (Laidre *et al*., 2008). Disturbance at important haul-out sites can cause repeated movements and increased energetic costs. Therefore, long-term conservation requires population monitoring, protection of critical feeding and haul-out habitats, regulated harvesting and reduction of anthropogenic disturbance.

**Conservation**

The walrus (*Odobenus rosmarus*) is currently classified as Vulnerable (VU) on the IUCN Red List (Lowry, 2016), indicating a high risk of extinction in the wild. Conservation efforts focus mainly on protecting Arctic sea-ice habitats, shallow-water feeding grounds and important haul-out sites. Climate change and declining sea ice are major concerns because walruses depend strongly on ice-associated habitats. Sustainable regulation of hunting is also important, particularly for populations subject to subsistence harvesting. Human disturbance from shipping, tourism and industrial activities should be minimized around major walrus aggregation sites. Pollution prevention, especially protection from oil spills, is also necessary to maintain healthy Arctic ecosystems. Regular population surveys, satellite tracking and ecological monitoring can help identify changes in distribution and population trends (Laidre *et al*., 2008). International cooperation among Arctic nations, researchers and Indigenous communities is essential for effective management. Overall, habitat protection, sustainable harvesting, scientific monitoring and climate-change mitigation are key measures for the long-term conservation of walruses.

**Conclusions**

The walrus is a remarkable Arctic marine mammal, uniquely adapted to its cold environment. Its specialized feeding, social behaviour and ecological role make it important to Arctic ecosystems. Protecting its habitat, reducing human disturbance and addressing climate change are essential for ensuring the long-term survival of this iconic species.

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# VULNERABILITIES IN INDIAN AGRICULTURE: STRATEGIC INTERVENTIONS FOR SUSTAINABLE GROWTH

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**Abstract**

Indian agriculture faces multiple and interconnected vulnerabilities arising from climate change, erratic rainfall, floods, droughts, declining soil health, groundwater depletion, imbalanced nutrient use, rising input costs, small and fragmented landholdings, market uncertainties, and inadequate access to institutional credit and extension services. These challenges threaten agricultural productivity, farmers' livelihoods, food and nutritional security, and the long-term sustainability of natural resources. This paper examines the major vulnerabilities affecting Indian agriculture and proposes strategic interventions for sustainable and resilient growth. Key priorities include climate-smart and regenerative agriculture, integrated soil fertility and water management, crop diversification, efficient input use, improved risk insurance, accessible institutional credit, strengthened farmer producer organizations, digital extension services, and better market infrastructure. It further emphasizes coordinated implementation of existing agricultural policies through village-level planning, institutional convergence, participatory decision-making, and outcome-based monitoring. An integrated, farmer-centric approach can reduce production risks, enhance resource-use efficiency, improve farm profitability, and strengthen the resilience of Indian agriculture while ensuring sustainable livelihoods and long-term food security.

**Keywords:** Agricultural vulnerabilities; Climate resilience; Sustainable agriculture; Soil health; Water management; Farmer livelihoods; Policy convergence; Resource-use efficiency

## Introduction

Agriculture remains a cornerstone of the Indian economy, providing livelihoods to a substantial proportion of the population and contributing significantly to national food and nutritional security. However, Indian agriculture faces multiple and increasingly interconnected vulnerabilities that threaten its productivity, profitability, and long-term sustainability. Climate change has intensified the risks associated with erratic monsoon rainfall, recurrent droughts, floods, heatwaves, and emerging pest and disease outbreaks. These climatic stresses interact with declining soil organic matter, nutrient imbalances, groundwater depletion, land degradation, and the unsustainable use of agricultural inputs, thereby weakening the resilience of farming systems. The vulnerability of Indian agriculture is further compounded by small and fragmented landholdings, rising cultivation costs, limited access to affordable institutional credit, inadequate extension services, price fluctuations, post-harvest losses, and insufficient market infrastructure. Smallholders, tenant farmers, women farmers, and resource-poor households are particularly exposed because their capacity to absorb production and market shocks is often limited. Consequently, increasing agricultural production alone is insufficient; development strategies must simultaneously address resource conservation, farm profitability, livelihood security, and environmental sustainability.

India has introduced several initiatives addressing these challenges, including the National Mission for Sustainable Agriculture (NMSA), the National Innovations in Climate Resilient Agriculture (NICRA) programme, the Soil Health Card Scheme, the Pradhan Mantri Fasal Bima Yojana, and programmes supporting micro-irrigation and farmer producer organizations. However, fragmented implementation and inadequate coordination among institutions can limit their effectiveness at the farm and village levels. This paper examines the major vulnerabilities affecting Indian agriculture and proposes strategic interventions encompassing climate-resilient farming, integrated soil and water management, crop diversification, efficient input use, improved extension services, accessible credit, risk management, and market development. Strengthening institutional convergence through participatory village-level planning is essential to achieving sustainable agricultural growth, resilient livelihoods, and long-term food security.

**Major agricultural vulnerabilities and their solutions**

Indian agriculture faces multiple interconnected vulnerabilities that threaten productivity, farm profitability, and livelihood security. Climate variability—including irregular monsoons, droughts, floods, heatwaves, and extreme rainfall—causes crop losses and increases production uncertainty. Climate-resilient varieties, diversified cropping systems, weather-based advisories, efficient irrigation, rainwater harvesting, and improved drainage can reduce these risks.

Soil degradation and imbalanced nutrient management contribute to declining soil fertility, nutrient-use inefficiency, and rising cultivation costs. Regular soil testing, balanced fertilization, integrated nutrient management, organic matter restoration, crop residue recycling, and site-specific nutrient application are essential for maintaining soil health.

Water scarcity and groundwater depletion require micro-irrigation, water budgeting, watershed development, farm ponds, and locally appropriate crop diversification. In waterlogged areas, drainage and conservation agriculture can improve soil aeration and protect crop productivity.

Small and fragmented holdings, rising input prices, and limited institutional credit constrain investment and technology adoption. Strengthening farmer producer organizations (FPOs), cooperative services, accessible credit, customized mechanization, and targeted financial support can improve economies of scale.

Market instability, inadequate storage, and post-harvest losses reduce farmers' incomes. Improved rural roads, warehouses, cold chains, processing facilities, market information, and transparent digital marketing can strengthen value chains.

Finally, inadequate extension services and fragmented policy implementation limit access to timely advice and support. Coordinated village-level planning involving agricultural departments, Krishi Vigyan Kendras, panchayats, FPOs, and financial institutions can integrate these interventions, enhance resilience, and promote sustainable agricultural growth. Table 1 identifies persistent structural challenges and emerging risks; their severity varies by region, crop, farm size and season.

**Table 1: Persistent structural challenges and emerging risks**

| Vulnerability | Major consequences for farmers | Sustainable solutions |
|---|---|---|
| 1. Climate change and extreme weather | Heatwaves, erratic monsoons, droughts, floods, | Climate-resilient varieties, diversified cropping, weather-based advisories, farm |

| Vulnerability | Major consequences for farmers | Sustainable solutions |
|---|---|---|
| | unseasonal rainfall and crop losses | ponds, drainage, mulching and timely sowing |
| 2. Excessive rainfall and waterlogging | Root damage, nutrient losses, delayed sowing, crop lodging and soil erosion | Field drainage, raised beds where suitable, community drainage plans, residue retention and post-flood nutrient assessment |
| 3. Groundwater depletion and water scarcity | Rising irrigation costs, falling water tables and unreliable supplies | Micro-irrigation where economical, irrigation scheduling, rainwater harvesting, groundwater budgeting and locally appropriate crop choices |
| 4. Declining soil health | Low soil organic matter, nutrient imbalance, compaction, salinity and reduced input efficiency | Soil testing, balanced fertilization, farmyard manure, compost, legumes, cover crops and conservation agriculture |
| 5. Imbalanced fertilizer use | Excessive or inadequate NPK, micronutrient deficiencies, lower nutrient-use efficiency and pollution | Soil-test-based integrated nutrient management, balanced NPK and secondary/micronutrients, appropriate fertilizer placement and split application |
| 6. Rising input costs | Reduced profit margins and higher financial risk | Efficient input use, collective purchasing, locally available organic resources, mechanization services and farm-level cost accounting |
| 7. Pests, diseases and pesticide resistance | Yield and quality losses, higher pesticide expenditure and harm to beneficial organisms | Integrated pest management (IPM), pest surveillance, resistant varieties, biological control and need-based pesticide use |
| 8. Small and fragmented holdings | Limited economies of scale and difficulty accessing machinery, storage and markets | FPOs, custom-hiring centres, shared machinery, collective marketing and cooperative post-harvest facilities |
| 9. Price volatility and market uncertainty | Distress sales, unstable income and uncertain investment decisions | Market information, diversified crops, storage, processing, collective marketing, suitable contracts and risk-management instruments |
| 10. Post-harvest losses | Spoilage, quality deterioration and reduced returns | Scientific storage, grading, packhouses, cold chains for perishables, processing and better transport |
| 11. Limited access to reliable information and technology | Delayed decisions, inefficient input use and uneven adoption of innovations | KVK demonstrations, local-language mobile advisories, digital soil records, accessible extension services and farmer field schools |

| Vulnerability | Major consequences for farmers | Sustainable solutions |
|---|---|---|
| 12. Labour shortages and mechanization gaps | Delayed sowing, harvesting losses and rising production costs | Small-farm machinery, custom hiring, women-friendly tools and locally suitable mechanization |
| 13. Indebtedness and inadequate risk protection | Financial stress after crop failure and limited capacity to invest | Transparent institutional credit, timely insurance settlement, financial literacy, diversified income and better access to markets |
| 14. Biodiversity loss and declining ecosystem services | Reduced pollination, fewer beneficial organisms and greater ecological vulnerability | Crop diversification, legumes, agroforestry, field margins, pollinator habitats and responsible pesticide use |
| 15. Weak coordination among agricultural institutions | Gaps between research recommendations and field-level implementation | Convergence among agriculture, irrigation, rural development, weather services, KVKs, panchayats and FPOs |

**Five interconnected problems requiring urgent attention**

**Climate vulnerability and unstable crop production:** Erratic monsoon rainfall, heat stress, floods, droughts and unseasonal rainfall can disrupt the entire agricultural calendar. The impact is especially serious when extreme weather coincides with flowering, grain filling, harvesting or land preparation for the next crop.

India's climate-risk assessment reported in March 2026 identified 310 of 651 assessed agricultural districts as highly or very highly vulnerable.

Recommended action plan

- Promote locally adapted, short-duration and stress-tolerant crop varieties.
- Diversify rice–wheat monocropping where agroecological and market conditions support alternatives.
- Prepare village-level drainage, drought-management and contingency-cropping plans.
- Use weather forecasts to guide sowing, irrigation, fertilizer application and harvesting.
- Combine crop insurance with preventive risk reduction and timely post-disaster assistance.

**Declining soil health and inefficient nutrient management:** Soil degradation, declining soil organic matter, erosion, nutrient imbalances and micronutrient deficiencies undermine productivity and fertilizer-use efficiency. In March 2026, the Government reported that zinc deficiency was particularly prominent in soils of Uttar Pradesh, Bihar and Odisha, while nitrogen and phosphorus status varied across Indian soils

Recommended action plan

- Test soil at appropriate intervals and follow crop-specific recommendations.
- Apply nitrogen, phosphorus and potassium in balanced proportions according to soil supply, crop demand and expected yield.
- Correct zinc, boron, sulphur and other deficiencies only where diagnosed or locally established.

- Integrate farmyard manure, compost, crop residues, legumes and suitable biofertilizers with mineral fertilizers.
- Minimize soil disturbance where appropriate, retain crop residues and prevent erosion.
- Evaluate fertilizer performance through yield, nutrient-use efficiency, farm profit and soil-health indicators—not yield alone.

**Water scarcity alongside excessive rainfall:** Indian farmers face the paradox of water shortages in some seasons and destructive excess rainfall in others. Over-extraction of groundwater threatens irrigation security, while waterlogging and runoff damage crops and remove valuable topsoil and nutrients.

The Government's 2026 reporting highlights the need to align cropping patterns with local water availability, particularly in groundwater-stressed regions.

**Recommended action plan**

- Develop farm ponds, recharge structures and village water-harvesting systems where technically suitable.
- Use drip or sprinkler irrigation where appropriate and economically viable.
- Schedule irrigation according to crop stage, soil moisture and weather.
- Improve field drainage before the monsoon and maintain community drainage channels.
- Promote millets, pulses, oilseeds, fodder crops and other suitable alternatives where water availability and market access justify diversification.
- Avoid indiscriminate pumping and encourage village-level groundwater budgeting.

**Rising costs, low profitability and market risks:** Higher expenditure on seed, fertilizers, pesticides, irrigation, machinery and labour can reduce net returns even when crop yields remain satisfactory. Smallholders may also lack storage, grading, processing and bargaining power.

**Recommended action plan**

- Calculate the full cost of cultivation and net returns for each crop.
- Reduce avoidable fertilizer, pesticide, water and energy expenditure through scientific recommendations.
- Strengthen FPOs and cooperatives for collective input purchasing, machinery hiring and produce marketing.
- Expand local processing, grading, storage and value addition.
- Improve access to reliable market information, institutional credit and suitable insurance.
- Diversify farm income through livestock, horticulture, agroforestry, beekeeping or other locally viable enterprises.

**Ecological degradation and overdependence on chemical inputs:** Excessive or poorly targeted agrochemical use, residue burning, continuous monocropping and loss of beneficial organisms can weaken ecosystem functions and increase long-term production risks.

**Recommended action plan**

- Adopt integrated pest management, using pesticides only when justified by monitoring and economic thresholds.
- Encourage crop rotations, legumes, cover crops and diversified cropping systems.
- Recycle crop residues and organic wastes safely.
- Protect pollinators, natural pest enemies, field margins and farm biodiversity.

- Reduce unnecessary fertilizer and pesticide losses through appropriate placement, timing and dosage.
- Evaluate regenerative practices scientifically, including their effects on yield, costs, soil carbon, water use and farmer income.

**From Vulnerable Farming to Sustainable and Regenerative Agriculture**

The transition from vulnerable farming to sustainable and regenerative agriculture requires a systematic shift from reactive responses to agricultural risks towards preventive, resource-efficient, economically viable, and ecologically sound farming systems. Indian farmers increasingly face interrelated challenges arising from climate variability, declining soil fertility, water scarcity, pest and disease outbreaks, rising cultivation costs, unstable market prices, and limited access to institutional support. These risks frequently reinforce one another, increasing production uncertainty and threatening household income and food security. Therefore, sustainable agricultural development must integrate improved agronomic practices with financial security, institutional coordination, collective action, and measurable environmental outcomes.

**Identify and assess agricultural risks*:*** The first step towards resilient farming is the systematic identification of risks at farm and village levels. Vulnerabilities differ according to agroclimatic conditions, soil types, water availability, cropping systems, farm size, household resources, and market access. Consequently, a uniform intervention package may not address the needs of all farming households.

Climate-related risks include delayed monsoon onset, prolonged dry spells, excessive rainfall, floods, heatwaves, and unseasonal weather during critical crop growth stages. Soil-related vulnerabilities include declining soil organic carbon, nutrient deficiencies or imbalances, soil erosion, compaction, salinity, and waterlogging. Water-related risks arise from declining groundwater levels, inefficient irrigation, inadequate drainage, and competition for water among agricultural, domestic, and industrial users. Pest and disease outbreaks can become more severe under changing climatic conditions, while excessive or poorly timed pesticide applications may increase production costs and environmental contamination.

Economic vulnerabilities are equally important. Rising prices of seeds, fertilizers, pesticides, energy, and labour can reduce farm profitability, particularly when output prices remain uncertain. Smallholders and tenant farmers may also experience difficulties accessing affordable credit, crop insurance, storage, transportation, and remunerative markets. Unexpected household expenditure can further restrict their capacity to purchase essential agricultural inputs or recover from crop failure.

A practical farm-risk assessment should therefore cover six interconnected dimensions: climate, soil, water, pests and diseases, markets, and household finances. Village-level risk maps, soil-test results, rainfall records, groundwater assessments, pest surveillance, crop-price information, and farmer consultations can help identify vulnerable locations and households. Krishi Vigyan Kendras (KVKs), agricultural departments, panchayats, farmer producer organizations (FPOs), and local financial institutions can jointly prepare seasonal risk-management plans. These assessments should be updated periodically to reflect changing weather patterns, cropping practices, resource availability, and market conditions.

**Adopt resilient and diversified farming practices:** Once major risks have been identified, farmers need locally appropriate practices that reduce exposure to shocks while maintaining productivity

and profitability. Crop diversification is a key strategy for reducing dependence on a single crop, particularly where monocropping increases vulnerability to weather extremes, pests, diseases, or price fluctuations. Depending on agroclimatic suitability and market demand, rice–wheat systems may be diversified with pulses, oilseeds, millets, fodder crops, vegetables, or other suitable alternatives. Intercropping, crop rotation, agroforestry, and integration of livestock can further diversify farm production and income sources.

Diversification should, however, be based on local water availability, soil suitability, labour requirements, market demand, and the expected costs and returns of alternative crops. Farmers should not be encouraged to replace established crops without access to suitable seed, technical guidance, procurement or marketing arrangements, and transition support.

Balanced nutrient management is another essential component of resilient agriculture. Repeated application of fertilizers without reference to crop requirements and soil nutrient status can cause nutrient imbalances, reduce nutrient-use efficiency, increase cultivation costs, and contribute to environmental pollution. Regular soil testing and soil-test-based fertilizer recommendations should guide the application of nitrogen, phosphorus, potassium, sulphur, and deficient micronutrients. Combining mineral fertilizers with farmyard manure, compost, suitable green manures, crop residues, and scientifically validated biofertilizers can support nutrient cycling and soil biological activity.

The objective is not simply to increase the proportion of organic inputs or reduce mineral fertilizers indiscriminately, but to supply crops with adequate and balanced nutrition while minimizing nutrient losses. Fertilizer application should be synchronized with crop demand, and placement, timing, irrigation, and application rates should be optimized wherever feasible.

Improved water management is particularly important under increasing rainfall variability and groundwater stress. Rainwater harvesting, watershed development, farm ponds, mulching, conservation tillage, and suitable micro-irrigation systems can improve water productivity. Irrigation scheduling based on crop growth stages, soil moisture, and weather conditions helps avoid unnecessary water application. In regions experiencing excessive rainfall, field drainage, raised beds where appropriate, and timely removal of excess water can reduce root-zone oxygen deficiency, nutrient loss, and crop damage. Water-saving technologies must be supported by appropriate crop choices and groundwater management so that efficiency improvements translate into actual resource conservation.

Integrated pest management (IPM) should combine resistant varieties, crop rotation, field sanitation, pest monitoring, biological control, and need-based pesticide applications. Economic thresholds should guide chemical interventions wherever established. Safe pesticide handling and protection of pollinators and beneficial organisms are also essential. Similarly, contour cultivation, vegetative barriers, cover crops, residue retention, and reduced soil disturbance, where suitable, can control erosion, conserve moisture, and protect soil structure. These practices should be adapted to local conditions rather than applied as a uniform package.

**Strengthen farmer institutions and support systems*:*** Agronomic improvements alone cannot ensure a successful transition if farmers lack access to credit, reliable advice, insurance, inputs, and remunerative markets. Institutional support is therefore fundamental to sustainable and regenerative agriculture.

Farmer producer organizations can help smallholders achieve economies of scale through collective procurement of quality inputs, shared machinery, aggregation of produce, grading, storage, processing, and collective marketing. By improving bargaining power and reducing transaction costs, effective FPOs can help farmers obtain better input prices and more favourable market terms. Their success depends on professional management, transparent governance, working capital, market linkages, and active participation by members.

KVKs and extension services should provide timely, location-specific guidance on climate-resilient varieties, soil-test-based nutrient management, water conservation, IPM, weather advisories, and regenerative practices. Demonstrations, farmer field schools, participatory trials, digital platforms, and community resource persons can improve the practical adoption of technologies. Extension programmes should also communicate the costs, benefits, limitations, and risks of proposed interventions instead of promoting technologies without adequate local validation.

Accessible institutional credit is required to finance quality seeds, irrigation equipment, machinery, livestock, storage, and post-harvest infrastructure. Credit delivery should account for seasonal cash flows and the requirements of tenant farmers, women farmers, and other groups who may face difficulties meeting conventional lending conditions. Crop insurance can provide an additional risk-management instrument, but its effectiveness depends on affordable premiums, transparent assessment, timely claim settlement, and awareness of policy provisions. Insurance should complement, rather than replace, preventive risk reduction.

Post-harvest and market infrastructure are equally important. Village-level storage, scientific warehouses, cold chains for perishables, processing facilities, rural roads, reliable market information, and accessible digital trading systems can reduce losses and improve market access. Linking diversification programmes with assured buyers, processing enterprises, suitable procurement arrangements, and FPO-led value chains can reduce the risk that farmers incur losses when shifting to alternative crops.

Coordination among agricultural departments, panchayats, KVKs, FPOs, banks, insurance providers, and market institutions should be organized through village-level agricultural development plans. These plans can align public programmes with local priorities, identify eligible beneficiaries, reduce duplication, and establish clear responsibilities for implementation and monitoring.

**Measure sustainable and regenerative outcomes*:*** Sustainable agriculture seeks to maintain productivity while conserving natural resources and supporting viable livelihoods. Regenerative agriculture places additional emphasis on progressively improving soil health, biological functioning, biodiversity, water regulation, and ecosystem resilience. Practices commonly associated with regeneration include maintaining soil cover, diversifying crop rotations, integrating organic amendments, reducing avoidable soil disturbance, improving nutrient cycling, and integrating trees or livestock where appropriate.

Nevertheless, regenerative agriculture should not be treated as a guaranteed outcome of adopting a particular practice or package. Results depend on soil type, climate, initial soil condition, crop choice, management quality, transition costs, and the time required for ecological processes to respond. Reduced tillage, residue retention, cover cropping, or organic amendments may offer substantial benefits in suitable settings, but each practice requires evaluation against local constraints, including labour availability, competing uses of crop residues, water requirements, and pest or disease risks.

Progress should be evaluated using measurable indicators rather than the regenerative label alone. Important indicators include:

- Productivity and profitability: crop yield stability, net returns, input costs, income diversification, and farm-income variability.
- Soil health: soil organic carbon, nutrient balance, soil structure, infiltration, erosion, and biological activity.
- Water management: water productivity, irrigation requirements, groundwater trends, and the frequency and severity of waterlogging.
- Environmental performance: nutrient-use efficiency, pesticide use, greenhouse-gas emissions where measurable, and nutrient losses to water bodies.
- Resilience and inclusion: recovery following climatic shocks, access to institutional services, participation of women and smallholders, and the effectiveness of collective marketing.

Baseline measurements and periodic assessments are necessary to distinguish genuine improvements from short-term fluctuations caused by weather or market prices. Monitoring should also account for the possibility of trade-offs, such as lower yields during transition periods, increased labour requirements, or the transfer of environmental pressures from one resource to another.

**An integrated pathway for transition:** The transition from vulnerable to sustainable and regenerative farming should proceed through a coordinated sequence: assess local risks, prioritize vulnerable households and resource constraints, select suitable agronomic interventions, secure institutional and financial support, and monitor results over successive seasons. Initial interventions may include soil testing, improved seed selection, drainage or water conservation, balanced nutrient application, and pest surveillance. Subsequent measures can expand into crop diversification, residue management, agroforestry, improved value addition, and collective marketing according to local feasibility.

Government programmes should support this process through convergence of climate-resilience initiatives, soil-health programmes, irrigation schemes, crop insurance, agricultural credit, extension services, and rural infrastructure development. Financial assistance and technical guidance should be tailored to farmers' transition costs and the expected time needed to realize benefits. Participatory planning is particularly important because farmers possess practical knowledge of local soils, water resources, labour constraints, and production risks.

The essential principle is to integrate agronomic improvements with economic security and collective action. Sustainable and regenerative agriculture will contribute to lasting progress when it delivers profitable and stable yields, healthier soils, efficient water use, reduced pollution, improved biodiversity, and stronger climate resilience without imposing unacceptable costs on vulnerable farming households. The ultimate objective is not merely to withstand agricultural shocks, but to develop farming systems that progressively strengthen their productive capacity, ecological foundations, and livelihood security.

**Policy and institutional measures**

India already has programmes that can support this transition. The challenge is to ensure effective, locally appropriate implementation and coordination.

- National Mission for Sustainable Agriculture (NMSA): strengthen rainfed farming, integrated farming systems and natural-resource conservation.

- National Innovations in Climate Resilient Agriculture (NICRA): expand climate-risk assessment, contingency planning and farmer demonstrations.
- Soil Health Card Scheme: translate soil-test results into practical, balanced nutrient management.
- Per Drop More Crop: improve irrigation efficiency where micro-irrigation is suitable.
- Pradhan Mantri Fasal Bima Yojana: improve accessibility, transparency and timeliness of eligible crop-loss compensation.

The Government's May 2026 account of NMSA describes these complementary approaches, including soil testing, micro-irrigation and climate-resilient farming interventions.

Further action should include:

1. Strengthening public agricultural extension and local-language digital advisories.
2. Supporting FPOs and custom-hiring centres for small and marginal farmers.
3. Linking research institutions, KVKs, panchayats and agricultural departments through village-level plans.
4. Improving access to affordable credit, reliable insurance and post-harvest infrastructure.
5. Monitoring sustainability through farm profitability, soil health, water productivity, input-use efficiency and resilience to weather shocks.

**5. Indicators for monitoring progress (See Table 3).**

**Table 3. Indicators for monitoring progress**

| Indicator | What to measure |
|---|---|
| Economic sustainability | Net farm income, cost of cultivation and income variability |
| Soil health | Soil organic carbon, pH, nutrient balance and erosion |
| Water sustainability | Water productivity, irrigation requirement and groundwater trends |
| Crop resilience | Yield stability and losses during adverse weather |
| Nutrient efficiency | Nutrient-use efficiency and nutrient balance |
| Ecological health | Crop diversity, beneficial organisms and pesticide-use trends |
| Social sustainability | Access to extension, credit, insurance, machinery and markets |

**Conclusion**

The most serious vulnerabilities facing Indian farmers arise from the interaction of climate instability, deteriorating natural resources, rising costs, market uncertainty and unequal access to technology and institutions. No single technology or scheme can solve these challenges. The way forward is a farmer-centred, climate-resilient and resource-efficient agricultural system that combines healthy soils, balanced plant nutrition, water security, diversified farming, integrated pest management, improved market access and effective risk protection. Sustainability should ultimately mean not merely maintaining crop yields, but progressively improving farm profitability, soil and water resources, ecological functioning and the capacity of rural households to withstand future shocks.

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# WINTER MANAGEMENT IN POULTRY: SCIENCE-BASED PRACTICES FOR HEALTHY AND PRODUCTIVE FLOCKS

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**Abstract**
Every winter, many poultry farmers notice the same pattern: birds eat more, lay less, and fall sick more often. The reason is simple. A cold bird burns its feed to stay warm instead of turning it into meat or eggs. Studies show that hens eat about 1% more energy for every degree the shed cools down, that broiler chicks kept a few degrees too cold are far more likely to die of ascites, and that sheds closed up tightly against the cold build up ammonia, which slows growth. In this article we explain, in plain terms, why winter is hard on birds. We then go through the practical steps that help most: a dry, draught-free shed with some fresh air, proper brooding heat, enough light for layers, slightly richer feed, warm drinking water, good litter, and timely vaccination. None of these steps is expensive and together they can save a farmer a good deal of money through the cold months.

**Keywords:** winter management, cold stress, poultry housing, brooding, lighting, ascites, ammonia, litter, biosecurity

## Introduction

Chickens are quite comfortable at moderate temperatures. Laying hens do best somewhere between 18 and 24 °C (Korkmaz, 2024). Day-old chicks need much more warmth, around 30 °C when they first arrive on the farm (Aviagen, 2020). India's winters vary a lot from place to place, from about 4 °C in some zones to nearly 29 °C in others (Ngullie, n.d.). For farmers in the north, the north-east and the hill areas, the months from November to February can be really tough on birds. Some of the losses are easy to see, like chicks piling up under the brooder or hens going off lay. Others are hidden. The feed bill quietly goes up, and closed sheds become damp and smelly. Diseases such as Ranikhet and infectious coryza also tend to show up more in the cold season (Saisai, 2025). Winter is also when migratory birds arrive and they can carry bird flu. The Government of India has a national action plan to keep this disease out of poultry farms (DAHD, 2021).

The good news is that most winter problems can be prevented. In the sections below, we look at what cold does to a bird's body, and then at simple things a farmer can do about housing, brooding, light, feed, water, litter and health.

## What cold does to a bird

A grown chicken can hold its body temperature steady, but a young chick cannot. Chicks only learn to manage their own body heat by around ten days of age (Yardımcı *et al*., 2006). Until then, the brooder is their only protection. Older birds deal with cold by fluffing up their feathers, crowding together, shivering and burning more feed for heat.

## More feed just to keep warm

This extra feed is the first cost of winter. In a careful study at 11, 16 and 21 °C, laying hens took in about 1% more energy for every one-degree fall in temperature (van Krimpen *et al*., 2014). Feathers

made a real difference. Hens with full plumage coped with the cold without producing extra heat, while hens that had lost half their feathers had to work harder to stay warm. So, a flock that is moulting or badly feather-pecked needs extra care in winter.

**Ascites in broilers**

Modern broilers grow very fast, and cold makes their bodies demand even more oxygen. The heart then has to push more blood through the lungs. When the lungs cannot cope, pressure builds up, the right side of the heart swells and water collects in the belly. This condition is called ascites or water belly (Wideman *et al*., 2013). In one trial, chicks were brooded about 4 °C cooler than normal for their first three weeks. They grew more slowly at first, and 9.52% of them died of ascites, compared with only 1.90% of chicks brooded at the right temperature (İpek and Şahan, 2006).

**Effect on immunity**

Cold does not always weaken a bird's immunity in a simple way. When growing chicks were kept at 10 °C for up to a week, their antibody levels stayed the same, though some immune cells became more active (Hangalapura *et al*., 2004). The bigger risk in practice comes from what usually goes with cold weather: closed sheds, damp litter and stale air.

**Can chicks be toughened up?**

Interestingly, a little cold early in life may help birds handle cold later. In a Turkish study, broiler chicks were kept at 15 °C for three hours on day 5 and day 6. Later, when the shed was cooled, only 5% of these birds died, against 11% of the others, and their growth and feed efficiency did not suffer (Yardımcı *et al*., 2006). This is still a research result, though and farmers should try it only on a vet's advice.

**How to tell your birds are cold**

Watch the flock closely. Cold birds huddle in corners or under the heater with their feathers fluffed up. Chicks crowd together, pile on each other and keep chirping loudly. The flock eats more, but weight gain or egg numbers do not improve and eggs may get smaller. In broilers, birds that die later in the batch with swollen bellies are a warning sign of ascites. Sneezing and wet nostrils usually mean the shed is too closed and the air is poor.

**Housing and ventilation**

In winter the shed has two jobs that pull in opposite directions. It must keep cold wind off the birds, but it must also let out moisture, ammonia and stale air. Because less water evaporates in cold weather, sheds tend to stay damp (Ngullie, n.d.), and that is where most winter trouble starts. The work should begin before the cold arrives. Walk around the shed and fix leaking roofs, broken walls and gaps under the doors, so the house stays dry and free of draughts (UF/IFAS, 2015). In open-sided houses, which are common in India, hang curtains of gunny bags, tarpaulin or plastic sheet. Do not simply drop them and forget them. Raise or lower them during the day as the weather changes (Aviagen, 2020). The most common mistake is to close the shed completely at night. Birds need a small amount of fresh air at all times, even on the coldest night (Aviagen, 2020). One easy way is to open the curtain slightly from the top rather than the bottom, so cold air enters above the birds and warms a little before it reaches them. If fans are used, keep them gentle, because strong air movement at bird level chills the flock (Aviagen, 2020). Keeping a few more birds in the shed, about 5% more than usual, helps them share body heat (Ngullie, n.d.), as long as the litter stays dry. In really cold areas, extra heat from bukharis, gas brooders or electric heaters is worth the cost

(Poultry India, n.d.). Keep heaters well away from litter and curtains. Any heater that burns fuel needs a proper outlet, because carbon monoxide should stay under 10 ppm and becomes harmful above 50 ppm (Aviagen, 2020). An open charcoal fire inside a closed shed should never be used.

**Brooding chicks in winter**

If there is one job a farmer must get right in winter, it is brooding. Chicks have no way of warming themselves, and a single cold night can undo weeks of effort. ICAR scientists note that brooding temperature matters most in winter and that backyard chicks may need brooding for four to six weeks (ICAR-NEH, n.d.). Even in commercial flocks, brooding usually has to run about a week longer than in summer (Saisai, 2025). Get the house ready a day ahead. Spread 2–3 inches of dry rice husk, sawdust or clean sand on the floor and cover it with old newspaper for the first few days (ICAR-DPR, n.d.). Switch the brooders on at least 24 hours before the chicks come, so the floor and the litter are already warm. When the chicks arrive, the air at chick height should be about 30 °C if the whole house is heated, or 32 °C at the edge of the brooder if only a corner is heated. The litter itself should be 28–30 °C, and humidity around 60–70% (Aviagen, 2020).

Humidity changes how warm the chicks actually feel. Winter air is often dry and in dry air the thermometer needs to read a little higher. Table 1 shows the temperatures recommended by one major breeding company at different humidity levels.

**Table 1. Recommended house temperature (°C) for broiler chicks by age and relative humidity (Aviagen, 2020)**

| Age (days) | At 50% RH | At 60% RH | At 70% RH |
|---|---|---|---|
| Day-old | 33.2 | 30.8 | 29.2 |
| 3 | 31.2 | 28.9 | 27.3 |
| 6 | 29.9 | 27.7 | 26.0 |
| 9 | 28.6 | 26.7 | 25.0 |
| 12 | 27.8 | 25.7 | 24.0 |
| 15 | 26.8 | 24.8 | 23.0 |
| 18 | 25.5 | 23.6 | 21.9 |
| 21 | 24.7 | 22.7 | 21.3 |
| 24 | 23.5 | 21.7 | 20.2 |
| 27 | 22.7 | 20.7 | 19.3 |

Thermometers help, but the chicks themselves tell you the most. If they are spread evenly around the brooder and quiet, all is well. If they bunch up under the heat and keep calling loudly, they are cold. If they move away to the walls and pant, they are too hot (Aviagen, 2020). A chick guard of cardboard or tin sheet keeps them close to the heat and away from cold corners. Farmers with a digital thermometer can also check vent temperature in the first four to five days; healthy chicks read between 39.4 and 40.8 °C (Aviagen, 2020).

**Lighting**

Hens decide when to lay mainly by the length of the day, not by the temperature. So, when winter days get short, egg numbers drop unless the farmer adds some artificial light.

For layers, the usual advice is 14 to 16 hours of light a day (Agro Advisory, 2024). The easiest way is to switch the bulbs on for a while before sunrise and again after sunset (UF/IFAS, 2015). Breeding companies give similar figures. Hy-Line, for example, expects its Brown hens to reach peak lay with 14–15 hours of light, and suggests adding 30 minutes a week, up to 16 hours, if the peak does not come (Hy-Line International, n.d.). Whatever schedule you choose, keep it steady. Cutting back the light during the laying period can quickly push birds off lay.

Broilers are different. They need light mainly to find feed and water. Local advisories in India suggest 23 hours of light and 1 hour of darkness for broilers (Agro Advisory, 2024). Breeder guidelines use this pattern for the first week only, and then recommend a dark period of 4–6 hours for better bird health (Aviagen, 2020). Keep the light bright, around 30–40 lux, in the first week, and at least 5–10 lux afterwards. Any change to the lighting should be made slowly, over two or three days (Aviagen, 2020).

**Feeding**

A bird uses its feed for two things: to keep its body warm and to grow, lay eggs and make feathers (Poultry India, n.d.). In winter, more of the feed goes to the first job, so the farmer has to make up the difference. It helps to put a rough number on this. Since hens eat about 1% more energy for each degree of cold (van Krimpen *et al*., 2014), a shed that sits at 11 °C instead of 21 °C means roughly 10% more energy per bird. That should be planned for in the feed budget, not discovered at the end of the month.

The simplest fix is a slightly richer ration. Feed with more energy, especially in the evening, helps birds get through long, cold nights (UF/IFAS, 2015). Maize is the usual energy source, and adding 1–2% vegetable oil also works well. Put up more feeders than in summer, and keep feed available through the whole day (Poultry India, n.d.), so that every bird, not just the strongest, can eat its fill before dark.

Vitamins and minerals should be kept at full levels, and extra vitamins can be given during cold spells or after vaccination on a vet's advice. Layers need enough calcium for good shells. Finally, look after the feed itself. Damp winter air encourages mould, so stack bags on wooden pallets off the floor and use each lot within a few weeks.

**Water**

Water is easy to forget in winter, because birds simply drink less when it is cold (Poultry India, n.d.). But a bird that drinks less also eats less, and production follows. Very cold water puts birds off drinking. The best drinking temperature is between 18 and 21 °C (Aviagen, 2020), so on cold mornings it is worth giving lukewarm water, especially to chicks and laying hens. Keep an eye on how much the flock drinks each day. At around 21 °C, broilers normally drink about 1.6 to 1.8 litres of water for every kilogram of feed they eat and a sudden fall or rise in water use is often the first sign that something is wrong (Aviagen, 2020).

Many vaccines, medicines and vitamins are given through the drinking water. Since birds drink less in winter, the farmer should reduce the volume of water the medicine is mixed in, so that each bird

still gets its full dose (Poultry India, n.d.). Lastly, check drinkers every day for leaks and set them at the right height. Spilled water is one of the main causes of wet litter in winter.

**Litter and air quality**

In winter, litter acts like a blanket on the floor. It has to be thick enough to keep the cold out and dry enough not to give off ammonia. A fresh, deep layer of at least 6 inches is advised for the winter months (Agro Advisory, 2024), and well-kept litter feels warm when you pick it up in your hand (Poultry India, n.d.). It is better not to clear out the shed completely in winter, because old built-up litter holds heat. If some must be removed, take out only part of it (Poultry India, n.d.). There is a simple hand test for litter. Squeeze a handful. It should not leave a finger mark or form a ball, and it should be neither dusty nor caked. Caked or wet patches should be taken out and replaced with fresh, dry material (ICAR-NEH, n.d.). Wet litter usually points to a bigger problem: leaking drinkers, too many birds, high humidity, poor ventilation, or a shed that is too cold (Aviagen, 2020). Ammonia is the hidden cost of a closed shed. Ideally, it should stay below 10 ppm. Above 20 ppm birds catch respiratory infections more easily, and above 25 ppm their growth can slow. Most people only start to smell ammonia at around 20 ppm (Aviagen, 2020), so if you notice the smell, the level is already too high. One study exposed broiler to 50 and 75 ppm of ammonia during their first four weeks. Their final weight was 6% and 9% lower, and at 75 ppm, 13.9% of the birds died, compared with 5.8% in clean air (Miles *et al*., 2004).

The lesson is simple: never give up fresh air for the sake of warmth. On cold nights, keep a little ventilation going and add heat if needed, rather than sealing the shed shut.

**Health care and disease prevention**

Cold weather, crowded sheds and stale air together give germs an easy time. Most winter losses come from breathing problems and gut infections. Ranikhet disease and infectious coryza in particular tend to show up more in the cold months (Saisai, 2025).

The best time to act is before winter starts. ICAR-DPR advises vaccinating rural poultry varieties in September–October, ahead of the cold (ICAR-DPR, n.d.). Local advisories also recommend vaccinating against Ranikhet disease and deworming birds every two months, in both backyard and commercial flocks (Agro Advisory, 2024). Each farm's vaccination plan should suit the diseases common in its own area, and every bird must get its full dose. Vaccines alone cannot save a flock that is poorly managed (Aviagen, 2020).

**Table 2. Common winter diseases of poultry and how to prevent them (based on Swayne *et al*., 2020)**

| Disease | What the farmer sees | How to prevent it |
|---|---|---|
| Chronic respiratory disease (CRD) | Sneezing, rattling breath, wet nostrils, poor growth | Buy Mycoplasma-free chicks, keep air fresh and ammonia low |
| Infectious coryza | Swollen face, foul-smelling discharge from the nose | Vaccinate where the disease is common, keep one age group per shed |
| Ranikhet (Newcastle) disease | Gasping, twisted neck, green droppings, sudden deaths | Vaccinate on schedule |

| Disease | What the farmer sees | How to prevent it |
|---|---|---|
| Infectious bronchitis | Coughing, fewer and poor-shelled eggs | Vaccinate, avoid chilling |
| Coccidiosis | Blood in droppings, dull and weak birds | Keep litter dry, use anticoccidials in feed |
| Bird flu (avian influenza) | Sudden heavy deaths, swollen comb and wattles | Strict biosecurity, report deaths to the vet at once |

Good biosecurity is cheap insurance. Keep all the birds in a shed of the same age, note down every visitor, and keep a footbath or hand wash at the shed door. Close any gaps that let in wild birds and stray animals (Aviagen, 2020). Rats and mice also look for warm places in winter, and a poultry shed suits them well, so rodent control needs extra attention at this time (Poultry India, n.d.).

Bird flu deserves special mention. India's national action plan stresses farm biosecurity, cleaning and disinfection, safe disposal of dead birds, and quick reporting of suspected cases (DAHD, 2021). If birds start dying suddenly, call the local veterinary officer straight away. Do not start antibiotics on your own without a proper diagnosis.

**Conclusion**

Winter does not have to mean losses. Cold makes birds eat more, can trigger ascites in broilers, and pushes farmers to close their sheds, which brings in ammonia and disease. But none of this is beyond control. A shed that is dry and free of draughts yet still gets some fresh air, chicks brooded at the right warmth, enough light for layers, a little extra energy in the feed, warm water, good litter, and vaccination done in time: these simple steps cover most of the risk. Farmers who prepare before the first cold night can keep their flocks growing and laying well, just when egg and chicken demand is at its highest.

**A quick checklist before winter**

- Shed repaired, curtains in place, no draughts at bird level
- Some fresh air allowed day and night
- Brooders switched on 24 hours before chicks arrive; temperature set by age (Table 1)
- Litter about 6 inches deep, dry and loose
- Layers getting 14–16 hours of light
- Richer feed and extra feeders arranged
- Lukewarm water in the mornings; daily water use noted
- Vaccination and deworming done; rodent control and biosecurity in place

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# WOMEN EMPOWERMENT THROUGH ORNAMENTAL VALUE-ADDED PRODUCTS: OPPORTUNITIES, ENTREPRENEURSHIP AND SUSTAINABLE LIVELIHOODS

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**Abstract**
Women empowerment through ornamental value-added products is an important approach to promoting entrepreneurship, employment generation and economic independence in the floriculture sector. Value addition involves converting fresh flowers and other ornamental plant materials into attractive and useful products, including bouquets, garlands, floral jewellery, dried flower arrangements, potpourri, handmade paper, natural dyes and floral crafts. These activities enable women to utilize their creativity, traditional skills and locally available resources to develop small-scale enterprises. With appropriate training, financial assistance, improved processing techniques and effective marketing, women can establish home-based businesses, participate in self-help groups and supply products to local markets, florists and online customers. Moreover, the utilization of suitable floral residues can help reduce waste and encourage environmentally responsible practices. However, limited access to finance, technical knowledge, quality packaging and reliable markets may restrict enterprise development. Strengthening training, institutional support and market linkages can improve business opportunities and promote sustainable livelihoods for women.

**Keywords:** Women empowerment, ornamental value addition, floriculture, entrepreneurship, self-help groups and rural livelihood.

## Introduction

Value addition in floriculture refers to the process of increasing the economic value, utility and consumer appeal of flowers and other floral materials through processing, preservation, product diversification, attractive packaging and improved marketing. It involves converting fresh flowers, petals, leaves, grasses, pods and other ornamental plant parts into useful and attractive products such as dried flower arrangements, potpourri, floral jewellery, bouquets, garlands, decorative handicrafts, petal-embedded handmade paper and other ornamental articles. Women empowerment refers to the process of enabling women to gain greater control over their economic resources, employment opportunities, skills, decision-making and participation in social and community development. In floriculture, women have traditionally contributed to flower cultivation, harvesting, sorting, garland making, bouquet preparation and other labour-intensive activities. However, their role can extend beyond production to include product development,

entrepreneurship, business management and marketing. Women empowerment through ornamental value-added products involves providing women with the knowledge, skills, resources and market opportunities required to transform flowers and floral materials into commercially valuable products. Through individual enterprises, self-help groups (SHGs), cooperatives and small-scale cottage industries, women can develop their creativity into productive economic activities and become more financially independent.

Compared with fresh flowers, properly processed dried floral products can have a longer shelf life and offer greater flexibility in storage, transportation and marketing. The production and sale of such products can therefore help diversify rural livelihoods, encourage self-employment and reduce the economic losses associated with the perishability of fresh flowers. Beyond income generation, ornamental value addition can contribute to women's social empowerment by strengthening their confidence, technical knowledge, entrepreneurial abilities and participation in collective decision-making. Participation in SHGs and other community-based organizations can facilitate access to training, shared equipment, financial services and wider markets. Such activities may also encourage women to take leadership roles, manage business earnings and participate more actively in household and community decisions.

**Steps for Starting a Value-Added Floriculture Business**

Starting a value-added floriculture business can provide women with opportunities for self-employment, creativity and financial independence. The first step is to identify a suitable product, such as dried flower arrangements, potpourri, floral jewellery, handmade paper or decorative flower products, according to personal skills, available resources and market demand. Practical training in flower preservation, floral crafts, processing, packaging and business management can help improve product quality. Women can explore suitable loans and government-supported entrepreneurship programmes to arrange the required capital. Establishing reliable relationships with local flower growers, suppliers and self-help groups helps ensure a regular supply of raw materials. Effective marketing through flower shops, exhibitions, social media, online marketplaces and event organizers can further expand the customer base. Careful planning, attractive packaging and consistent quality are essential for developing a successful and sustainable enterprise.

**Income Generation through Floral Value Addition**

Women can generate income from value-added floral products through different marketing and service activities. Direct selling at local markets, exhibitions, craft fairs and retail outlets provides opportunities to reach customers and receive immediate payments. Online marketing through social media and e-commerce platforms allows women to promote their products beyond their local areas. They can also supply customized floral arrangements, decorative crafts, fragrances and suitable floral products to hotels, spas, wedding planners and event management companies. Regular orders and subscription-based product packages may help provide a more consistent source of revenue. In addition, women with technical expertise can organize training programmes and workshops on bouquet making, dried flower crafts and other floral products. Diversifying sales channels and controlling production costs can improve business stability and profitability.

**Role of Women in the Floral Value Addition Industry**

Women play an important role in the floral value addition industry through their creativity, technical skills, entrepreneurship and contribution to sustainable development. They transform flowers and other ornamental materials into attractive products that meet the needs of different customers.

Their innovative designs and traditional craftsmanship help develop distinctive products for festivals, weddings, decoration and gifting. Women can also promote environmentally responsible practices by utilizing suitable floral residues, reducing avoidable waste and adopting appropriate packaging materials. Through the establishment of small enterprises and participation in self-help groups, they create employment opportunities for other women and contribute to local economic development. Managing their own businesses can strengthen women's confidence, leadership abilities, financial independence and participation in decision-making. Thus, women are not only producers of floral products but also entrepreneurs and community leaders who help connect floriculture with livelihood development and economic empowerment.

**Major Ornamental Value-Added Products for Women Entrepreneurship**

**Fresh flower value-added products**

Fresh flower value-added products include bouquets, baskets, bunches, buttonholes, corsages, garlands, floral strings, wreaths, gajras, venis and floral jewellery. These products are prepared by arranging fresh flowers and foliage in attractive designs for decoration, gifting, weddings, festivals and religious occasions. They provide opportunities for women to develop small-scale businesses using their creativity and locally available flowers.

**Floral Arrangement:** Floral arrangement is the art of arranging cut flowers and foliage in a container to create an attractive design. Roses, carnations, chrysanthemums, lilies and gerberas are commonly used. Floral arrangements are used for home decoration, weddings, hotels, offices and special occasions. Women can earn income by preparing customized arrangements according to customer preferences.

Floral arrangement provides opportunities for women to work as independent floral designers, supply decorative products to event organizers and develop customized businesses for celebrations and gifting.

**Bouquets:** A bouquet is a decorative arrangement of flowers presented as a gift or used for special occasions. Bouquets may be round, cascading, crescent-shaped or hand-tied. Flowers such as roses, gerberas, lilies, carnations and gladiolus are commonly used with suitable foliage and decorative wrapping. They are popular for birthdays, weddings, anniversaries and formal ceremonies.

Bouquet making is a suitable small-scale enterprise for women because it requires floral design skills, careful handling and creativity, while allowing products to be customized for different customers and budgets.

**Rangoli:** Rangoli is a traditional Indian decorative art used during festivals, weddings and religious functions. Floral rangoli is prepared using colourful flower petals, whole flowers and green foliage instead of artificial colours. Rose, marigold and chrysanthemum petals are commonly used to create attractive patterns. Women can provide floral rangoli and event decoration services to generate income.

**Garlands:** Garlands are made by joining flowers together with thread using a needle or other suitable techniques. They are used during religious ceremonies, festivals, weddings and welcoming functions. Roses, marigolds, jasmine, tuberose and chrysanthemums are commonly used. Garland making is a traditional, home-based activity that provides employment opportunities for women.

Garland making supports regular employment and income generation, particularly in areas where flowers are readily available and traditional demand remains strong.

**Buttonhole:** A buttonhole, also called a boutonniere, is a small floral arrangement worn on the lapel of a suit or jacket. It generally consists of a single flower, such as a rose or carnation, combined with a small piece of foliage. Buttonholes are used during weddings, formal ceremonies and special events. Women can prepare customized designs according to customer requirements.

Buttonhole preparation allows women to produce small, customized floral accessories with relatively little raw material. Matching the design and colour to the customer's clothing or event theme can increase its appeal.

**Corsage:** A corsage is a small decorative arrangement of flowers worn on the wrist or attached to clothing. It is generally more elaborate than a buttonhole and may contain roses, orchids, carnations and foliage. Corsages are commonly used at weddings, anniversaries, parties and other special occasions. Their customized preparation provides opportunities for women entrepreneurs.

Corsage making encourages creativity and allows women to develop specialized floral accessories for customers seeking personalized products.

**Wreath:** A wreath is a circular arrangement of flowers, leaves or foliage used for decoration and ceremonial purposes. It may be prepared from fresh or dried flowers, depending on its intended use. Wreaths are used for home decoration, festivals, weddings and memorial services. Women can prepare decorative wreaths using locally available floral materials.

Wreath making provides opportunities to combine floral design with decorative craftsmanship and develop products for both traditional and contemporary markets.

**Gajra:** A gajra is a traditional Indian floral ornament used to decorate women's hair. It is generally made by stringing jasmine, tuberose or other fragrant flowers together in a circular or chain-like form. Gajras are popular during weddings, festivals and religious occasions. Their preparation provides income opportunities for women through local flower markets and bridal services.

Gajra making preserves traditional floral craftsmanship and provides a practical income-generating activity for women, particularly in markets where floral hair ornaments are in regular demand.

**Veni:** A veni is a long floral ornament used to decorate braided hair, particularly during South Indian weddings, religious functions and classical dance performances. It is commonly prepared using jasmine and other suitable flowers arranged along a long base. The length and design can be customized according to the hairstyle and occasion. Veni making helps preserve traditional floral craftsmanship while supporting women's self-employment.

Veni making offers a way to preserve regional floral traditions while creating opportunities for women to earn income through skilled, home-based production.

**Dry flower value-added products**

Dry flower value-added products are prepared by drying and preserving flowers, petals, leaves, grasses and other ornamental plant parts for use in decorative and craft items. Flowers such as rose, chrysanthemum, gomphrena, statice, helichrysum and delphinium can be dried using suitable techniques and arranged in vases, bouquets, wall hangings and other decorative articles. These products have a longer shelf life than fresh flowers and provide opportunities for women to develop small-scale businesses with suitable training and market support.

**Potpourri:** Potpourri is a mixture of dried flowers, aromatic leaves, spices, seeds and other fragrant materials used to provide a pleasant aroma and decorative appeal to rooms. Rose petals, marigold, lavender, jasmine and other aromatic flowers are commonly used. Natural or suitable commercial fixatives may be added to help retain the fragrance. Potpourri can be packed in decorative bowls, sachets or pouches and sold as a home-fragrance product.

Women can prepare potpourri using suitable locally available flowers and aromatic materials. Attractive packaging and customized fragrances can help them sell these products through gift shops, exhibitions and online markets.

**Candles:** Dried flowers can be used to decorate candles and create attractive ornamental products. Rose petals, lavender and calendula are examples of flowers used in decorative candle designs. Dried floral materials may be incorporated into suitable outer decorative layers or candle holders; they should not be placed near the flame or wick where they could ignite.

Decorative candle making allows women to combine floral crafts with candle-making skills and develop products for festivals, weddings, home decoration and gifting. Safe production techniques, attractive designs and suitable packaging are essential.

**Pressed Dried Flower Products:** Pressed flower products are prepared by flattening and drying flowers and leaves, often using a flower press or absorbent paper. The preserved materials are arranged artistically and attached to suitable surfaces to prepare bookmarks, greeting cards, wall hangings, table mats, decorative frames and other handicrafts.

Pressed flower crafts can be produced on a small scale with relatively simple equipment. Women can develop customized designs and sell them as handmade gifts, souvenirs and decorative articles. Proper drying and protection from moisture help maintain the appearance of the products.

**Processed flower products**

Processed flower products are prepared by converting suitable flowers and petals into useful products through extraction, preservation or other processing methods. These include essential oils, rose water, gulkand, floral teas, natural dyes, cosmetics and other floral preparations. Such products can provide additional uses for selected flower crops and create opportunities for women to participate in processing, packaging and marketing. Food, cosmetic and fragrance products require appropriate hygiene, quality control and compliance with applicable safety requirements.

**Gulkand:** Gulkand is a traditional preparation made by combining rose petals with sugar and allowing the mixture to mature under suitable conditions. It is valued for its sweet taste, characteristic aroma and traditional culinary uses. Suitable fragrant rose varieties are selected for preparation, and clean petals are used to maintain product quality.

Women can prepare and market gulkand in properly sealed containers as a traditional food product. Good hygiene, consistent quality, suitable packaging and compliance with food safety requirements are important for developing a successful enterprise.

**Floral Tea:** Floral tea is prepared by infusing suitable edible flowers or petals in hot water, either alone or in combination with other ingredients. Rose, chamomile, jasmine and chrysanthemum are used in certain floral tea preparations, depending on the product and local practices. The flowers must be correctly identified and suitable for consumption, with attention to pesticide residues and food safety.

Women can explore floral tea products for specialty food markets and gift packs. Proper drying, hygienic handling, attractive packaging and verified food safety can help develop consumer confidence.

**Gulroghan and Pankhuri:** Pankhuri refers to rose petals that may be dried and used in suitable traditional preparations, sweets or decorative applications. Gulroghan is traditionally associated with a rose-based fragrant oil preparation. The exact preparation method and ingredients may vary according to the traditional formulation.

These traditional products can offer opportunities for women to preserve local knowledge and develop specialized products for appropriate markets. Standardized preparation, ingredient quality and clear product labelling are important for commercial production.

**Bathing and Other Body-Care Products:** Suitable dried flowers and petals are used in decorative bath preparations and certain body-care products. They may be incorporated into bath sachets, herbal bath mixtures and other formulations. Flower extracts may also be used in selected soaps, lotions and cosmetic preparations when their suitability and safety have been established.

Floral body-care products can provide opportunities for women to develop niche businesses based on fragrance, appearance and product presentation. Formulation safety, ingredient quality, hygiene, labelling and applicable cosmetic regulations must be considered.

**Conclusion**

Ornamental value addition in floriculture offers promising opportunities for empowering women through skill development, self-employment and enterprise creation. Products such as floral arrangements, garlands, gajras, dried flowers, potpourri, decorative crafts and petal-embedded handmade paper can transform locally available floral materials into marketable commodities. These activities can be undertaken at household or community levels, making them suitable for women with different levels of investment and technical expertise. Training programmes, access to credit, improved processing methods, attractive packaging and digital marketing can help women improve product quality and reach wider markets. Furthermore, self-help groups and cooperative enterprises can encourage collective production, resource sharing and better bargaining power. Sustainable utilization of flowers and floral residues can also contribute to waste reduction and resource efficiency. Therefore, coordinated efforts from government agencies, educational institutions and financial organizations are essential to strengthen women-led floriculture enterprises and support long-term economic and social empowerment.

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# ORGANIC FARMING IN ARID REGIONS: OPPORTUNITIES, CHALLENGES AND STRATEGIES FOR SUSTAINABLE AGRICULTURE

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## Introduction

Arid and semi-arid agroecosystems cover over 40% of the Earth's terrestrial surface and host more than two billion people. Characterized by low, erratic precipitation, severe evapotranspiration rates, fragile topsoils and extreme thermal fluctuations, these drylands are acutely vulnerable to desertification and climate disruptions. Decades of conventional agriculture-relying heavily on groundwater over-extraction, synthetic nitrogenous fertilizers, and aggressive chemical pesticides-have accelerated soil salinization and depleted already marginal soil organic matter (SOM).

Organic farming represents not merely an input-substitution model in drylands, but an ecological design framework. By emphasizing soil biological regeneration, natural moisture conservation and biodiversity-driven resilience, organic systems offer a viable pathway to sustain food production without depleting the natural resource base.

## Distinct Opportunities in Drylands

While arid zones present harsh agronomic conditions, they possess specific structural and environmental features that naturally align with organic farming systems.

- **Naturally Low Baseline Agrochemical Use:** In many hyper-arid and arid zones, resource constraints and drought risks have historically discouraged heavy expenditures on synthetic inputs. Many dryland farmers practice traditional "organic by default" farming. The transition barrier to certified organic agriculture is often lower here than in intensively farmed alluvial or sub-humid regions.
- **Low Relative Humidity and Natural Pest Suppression:** High diurnal temperatures combined with very low ambient humidity substantially suppress fungal spore propagation and airborne foliar pathogens (such as mildews and blights). This naturally minimizes the need for bio-fungicides and sulfur or copper-based sprays.
- **Niche Cultivation of High-Value Dryland Flora:** Arid tracts are rich in specialized, deep-rooted germplasm with substantial global commercial value:
    - Medicinal and Aromatic Plants (MAPs): Senna (*Cassia angustifolia*), Ashwagandha (*Withania somnifera*) and Isabgol (*Plantago ovata*).
    - Resilient Spices and Pulses: Cumin, coriander, fenugreek, cluster bean (guar), moth bean (*Vigna aconitifolia*), and drought-hardy millets (pearl millet, proso millet).
    - Organic premiums for these exportable commodities frequently offset baseline yield fluctuations.
- **Enhanced Soil Carbon Sequestration:** Increasing soil organic carbon (SOC) yields

disproportionately large benefits in dry soils. Every incremental increase in SOM elevates water retention capacity exponentially, making arid soils the most responsive ground for biological regeneration.

**Fundamental Agronomic and Structural Challenges**

Transitioning to and sustaining an organic production model in water-stressed environments entails severe systemic hurdles.

| Domain | Primary Constraint | Agronomic Impact |
|---|---|---|
| **Biomass Scarcity** | Low net primary productivity (NPP) | Severe shortage of organic amendments, green manure, and crop residue for composting. |
| **Nutrient Mineralization** | Soil moisture deficit | Organic fertilizers require microbial digestion and moisture to release nutrients; dry soils cause nutrient lockup. |
| **Secondary Salinization** | High capillary rise and evapotranspiration | Organic amendments without optimal water management can concentrate salts in the upper root zone. |
| **Thermal Degradation** | Soil surface temperatures >50 °C | Rapid thermal oxidation of newly added compost and degradation of surface microbial inoculants. |
| **Conversion Yield Lag** | Depleted microbial baselines | Extended transitional yield dips (2–3 years) before soil microflora fully recovers, threatening smallholder cash flow. |

**Core Strategies for Sustainable Arid Organic Agriculture**

Bridging the gap between ecological theory and arid realities demands tailored, resource-conserving technologies.

**Integrated Soil Moisture and Organic Carbon Engineering**

Water and soil carbon must be managed as a single, linked system:

- **Biochar Integration:** Pyrolyzing dry scrub biomass (such as *Prosopis juliflora*) creates recalcitrant biochar. When co-composted with farmyard manure (FYM), biochar increases water-holding capacity, expands cation-exchange capacity (CEC), and stays stable in hot soils for decades without rapid thermal volatilization.
- **Mulching with Inorganic–Organic Hybrids:** In regions where straw is reserved for livestock fodder, farmers utilize pebble mulching or border rows alongside biological residues to shield the soil surface, suppress evaporation, and moderate soil temperatures.
- **In-Situ Moisture Harvesting:** Land manipulation via broad-bed and furrow (BBF) systems, tied-ridging, contour bunding, and *khadin* runoff-harvesting architectures concentrates sparse rainfall directly into the crop root zone.

**Tailored Crop Diversification and Dryland Agroforestry**

Monocultures collapse rapidly under arid climatic shocks. Resilient organic dryland systems rely on vertical and temporal stratification:

- **Agri-Silvi-Pastoral Models:** Integrating multipurpose perennial trees—such as *Khejri* (*Prosopis cineraria*), *Ber* (*Ziziphus mauritiana*), Acacia, and Drumstick (*Moringa oleifera*)—provides windbreaks, fixes nitrogen, yields off-season fodder, and reduces wind erosion

while preserving field-edge microclimates.

- **Legume-Dominant Crop Rotations:** Intercropping deep-rooted cereals (e.g., Pearl Millet) with drought-hardy legumes (Moth bean, Cowpea, Cluster bean) ensures biological nitrogen fixation and continuous ground cover without requiring synthetic N inputs.

**Customized Biological Nutrient Formulations**

Standard composting methods often lose nitrogen through ammonia volatilization under hot winds. Dryland systems benefit from closed-vessel and liquid fermentations:

- **Liquid Biostimulants and Biofertilizers:** Fermented organic formulations using cow dung, urine, pulse flour, and virgin forest/rhizosphere soil (such as *Jeevamrit* or *Beejamrit*) provide active consortia of plant-growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and organic acids that unlock native rock phosphate in alkaline arid soils.
- **Foliar Nutrition:** Applying diluted vermiwash and seaweed/humic extracts directly onto leaves delivers micro- and macronutrients without depending entirely on soil-water transport during dry spells.

**Policy, Institutional, and Market Enablers**

Agronomic solutions must be underpinned by structured market mechanisms to ensure economic viability for dryland producers:

- **Decentralized Certification Frameworks:** Third-party certification costs remain prohibitive for marginal dryland farmers. Scaling Participatory Guarantee Systems (PGS) enables community-level compliance verification, reducing administrative overhead while maintaining local traceability.
- **Ecosystem Service Payments:** Public policy should incentivize dryland organic farming through direct ecosystem service compensations for soil carbon sequestration, water table preservation, and the protection of biodiversity corridors.
- **Value Addition at Origin:** Processing dryland commodities locally (e.g., cold-pressing mustard, processing guar gum, de-husking and milling millets) protects producers from middleman exploitation and ensures export-grade standards are met before transport.

Organic farming in arid regions is not merely an alternative crop-management technique; it is an ecological imperative for dryland restoration. While moisture deficits and biomass limitations present genuine friction, combining traditional dryland conservation practices with modern bio-enhancements-such as biochar, agroforestry, and tailored biostimulants-transforms arid agriculture into a climate-resilient, economically viable enterprise.

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