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INVASIVE FISH SPECIES AND INLAND FISHERIES RESOURCE MANAGEMENT STRATEGIES FOR SUSTAINABLE FISH PRODUCTION

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Introduction

Inland fisheries are an important component of food security, livelihoods, nutrition, and aquatic ecosystem services, particularly in regions where rivers, lakes, reservoirs, wetlands, ponds, and floodplain ecosystems support diverse fish communities. However, these resources are increasingly affected by habitat degradation, pollution, climate change, overexploitation, and the introduction and spread of non-native fish species. Invasive fish species can establish self-sustaining populations and alter native aquatic communities through competition, predation, habitat modification, food-web disruption, and disease or pathogen transmission. In India, several non-native fishes have become established in rivers, wetlands, reservoirs, and other open waters, creating concerns for native biodiversity and fisheries resources. The spread of these species is associated with activities such as aquaculture, ornamental fish trade, intentional stocking, accidental escape, and movement through connected water bodies. Recent evidence also indicates that invasive fish populations can interact with other environmental pressures, making their ecological effects more complex. Their impacts may extend beyond biodiversity loss to changes in ecosystem functioning, fisheries productivity, and the livelihoods of fishing communities (Azzurro *et al*., 2024). Once invasive populations become well established, complete eradication can be difficult or impractical, emphasizing the importance of prevention and early intervention. Effective management therefore requires risk assessment, regulation of introductions, biosecurity, early detection, continuous monitoring, and appropriate control measures. At the same time, fisheries management should consider ecological conditions and the socioeconomic importance of inland fisheries while reducing the further spread of invasive species. Thus, integrated management approaches that combine prevention, monitoring, habitat restoration, responsible fisheries practices, and community participation are essential for protecting native fish diversity and maintaining sustainable inland fish production.

Invasive fish species in inland fisheries

Invasive fish species are non-native fishes that establish self-sustaining populations and spread beyond their original range, potentially affecting native biodiversity, ecosystem functioning, and fisheries resources. Indian inland waters, including rivers, reservoirs, lakes, wetlands, and floodplain ecosystems, have experienced the introduction and establishment of several non-native fishes. Recent evidence has documented numerous non-native fish species across major Indian river basins, with *Cyprinus carpio* and *Oreochromis mossambicus* among the most widely reported species. Their establishment is influenced by biological characteristics, environmental conditions, and human-mediated introduction pathways. Understanding the occurrence, pathways, establishment, and spread of these species is essential for developing effective fisheries management and conservation strategies.

Major invasive fish species

Several non-native fishes are established or widely reported in Indian inland waters, including common carp (*Cyprinus carpio*), Mozambique tilapia (*Oreochromis mossambicus*), Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), and suckermouth armored catfishes (*Pterygoplichthys* spp.). Other introduced species include silver carp (*Hypophthalmichthys molitrix*), bighead carp (*H. nobilis*), grass carp (*Ctenopharyngodon idella*), rainbow trout (*Oncorhynchus mykiss*), and mosquito fish (*Gambusia affinis*). These species differ in their distribution, abundance, ecological interactions, and effects on fisheries. Traits such as high reproductive capacity, rapid growth, broad dietary preferences, environmental tolerance, and behavioural flexibility can favour establishment under suitable conditions. However, not every introduced or non-native species becomes invasive; therefore, invasion status should be assessed using evidence of establishment, spread, ecological effects, and population dynamics.

Pathways and causes of invasion

The introduction and spread of non-native fishes are strongly associated with human activities such as aquaculture, fish stocking, cage culture, ornamental fish trade, aquarium releases, intentional introductions, and accidental movement between water bodies. Escape from aquaculture and cage-culture facilities can provide direct opportunities for non-native fishes to enter natural ecosystems, particularly where culture facilities are located near rivers, reservoirs, or wetlands. Floods, canals, and connected waterways can subsequently facilitate their dispersal into new habitats. Inadequate biosecurity, unregulated live-fish movement, inappropriate stocking practices, and intentional release may further increase invasion risks. Environmental changes, including habitat degradation, pollution, altered hydrological conditions, and increasing temperatures, may also create favourable conditions for some non-native species. Therefore, prevention requires risk assessment, quarantine, responsible stocking, secure culture systems, regulation of live-fish movement, and effective biosecurity measures (Cowx *et al*., 2019).

Establishment and spread in inland waters

Successful establishment of an invasive fish depends on its ability to survive, reproduce, recruit, and maintain viable populations under local environmental conditions. Suitable temperature, food availability, habitat characteristics, water quality, reproductive opportunities, and hydrological connectivity can influence establishment and population growth. Species with high reproductive output, flexible feeding behaviour, rapid growth, and tolerance to environmental fluctuations may expand rapidly once suitable habitats are occupied. Their subsequent spread can occur through rivers, canals, reservoirs, wetlands, flood events, and human-mediated fish movement. Interactions with native fishes, including competition for food and habitat, predation, and dietary overlap, may further influence their population expansion and ecological effects. Continuous fish surveys, catch monitoring, environmental DNA, GIS-based distribution mapping, and community-based reporting can support early detection and monitoring. Early identification and rapid management of newly established populations are particularly important because controlling widely distributed populations is generally more difficult than preventing introduction and containing early-stage invasions.

Impacts of invasive fish species on inland fisheries

Invasive fish species can produce ecological, economic, and fisheries-related impacts after establishing viable populations in inland water bodies. Their effects depend on species

characteristics, population abundance, habitat conditions, and interactions with native communities. Invasive fishes may alter food-web structure, compete with native species for food and habitat, prey on native fishes and other aquatic organisms, and modify nutrient cycling and habitat conditions. These changes can reduce native fish diversity and alter the composition and productivity of aquatic communities. In fisheries systems, high abundance of invasive species may also affect the availability of commercially important native fishes and influence catch composition and fishing practices. Therefore, assessment of invasive species impacts should consider both ecological changes and consequences for fish production and dependent communities (Singh *et al*., 2025).

Impacts on native fish biodiversity

Invasive fishes can affect native fish biodiversity through competition, predation, habitat modification, and alteration of food-web relationships. Species with overlapping feeding or habitat requirements may compete with native fishes for food, spawning areas, shelter, and other resources, particularly when invasive populations reach high abundance. Predatory invasive fishes may directly consume eggs, larvae, juveniles, or adults of native species, while highly adaptable species can occupy habitats that were previously dominated by native communities. These interactions may change community structure, reduce the abundance of sensitive species, and contribute to shifts in species composition. The effects can be particularly important in degraded or disturbed inland ecosystems where native fish populations are already under pressure from habitat loss, pollution, overfishing, and other environmental stressors.

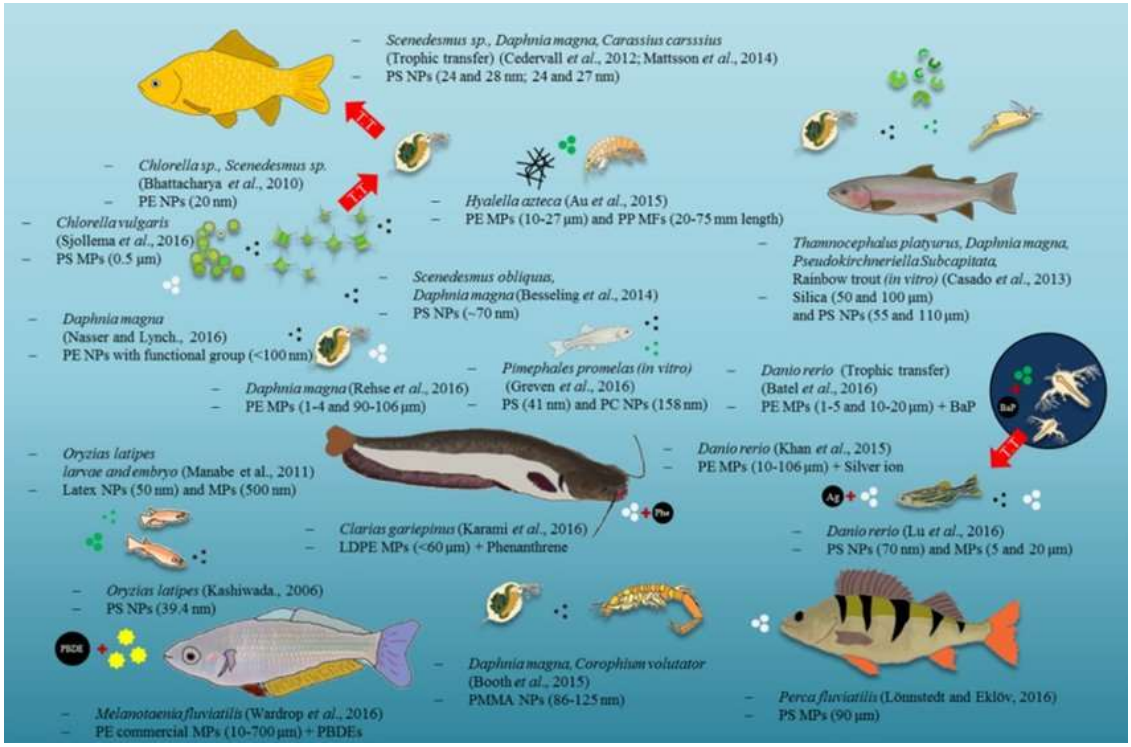


Figure 1. Toxic effects of micro- and nanoplastics on freshwater biodiversity.

Impacts on fish production and livelihoods

The establishment of invasive fishes can influence inland fisheries production by changing catch composition, reducing the relative abundance of commercially valuable native species, and altering

fishing practices. However, the effect on total fish production is not necessarily uniform because some non-native fishes may themselves contribute substantially to fish catches or provide economic value in particular systems. The important management issue is therefore to distinguish between increased biomass and sustainable production of desirable fish communities. Changes in species composition may affect fishers through variations in market value, fishing gear requirements, catch handling, and consumer acceptance. Consequently, fisheries assessments should consider species-specific catch trends, economic value, livelihood dependence, and long-term changes in native fish populations rather than relying only on total fish production.

Ecological and economic consequences

The ecological and economic consequences of invasive fish species are interconnected because changes in aquatic communities can influence fisheries productivity, ecosystem services, and the livelihoods of fishing-dependent communities. High-density invasive populations may increase management and monitoring costs, require additional control measures, and create conflicts where their ecological effects differ from their economic value. At the ecosystem level, changes in species composition, trophic interactions, nutrient dynamics, and habitat use may reduce ecological resilience and complicate fisheries management. Therefore, invasive fish management should adopt an ecosystem-based approach that evaluates biodiversity, fish production, economic benefits, and potential long-term ecological costs together. Such assessment can provide a scientific basis for developing management measures that protect native fish resources while maintaining sustainable inland fisheries production.

Inland fisheries resource management strategies

Effective management of invasive fish species requires an integrated approach that combines prevention, early detection, monitoring, control, habitat management, and participation of local communities. Management measures should be based on the biology and distribution of the target species, characteristics of the invaded ecosystem, potential ecological impacts, and socioeconomic conditions. Because invasive populations are often difficult to eradicate after widespread establishment, priority should be given to preventing new introductions and detecting emerging populations at an early stage. Where established populations cannot be completely removed, management can focus on reducing their abundance, limiting further spread, protecting vulnerable native species, and restoring ecosystem functions. Integration of conventional fisheries surveys with modern tools such as environmental DNA, GIS, remote sensing, molecular identification, and digital monitoring can strengthen surveillance and support evidence-based management decisions.

Early detection and monitoring

Early detection is one of the most important components of invasive fish management because identifying newly introduced populations before they become widely established can increase the effectiveness of containment and control measures. Regular fish sampling, catch monitoring, environmental DNA (eDNA), molecular identification, GIS-based distribution mapping, and community-based reporting can be used to detect changes in species occurrence and abundance. Monitoring should particularly focus on high-risk locations such as aquaculture facilities, reservoirs, wetlands, fish markets, ornamental fish release sites, and hydrologically connected water bodies. Long-term monitoring can also identify changes in population density, reproduction, distribution, and interactions with native species. Standardized sampling methods and centralized databases are important for comparing information among locations and supporting timely management responses.

Control and removal strategies

Control measures should be selected according to the invasive species, population density, habitat characteristics, and potential effects on native communities. Mechanical removal using appropriate fishing gears, trapping, targeted harvesting, and repeated removal can reduce invasive fish abundance in suitable water bodies. In some situations, changes in fishing practices or targeted utilization may provide an additional means of reducing populations, although such approaches require careful assessment to avoid creating incentives for further propagation. Chemical or biological control methods require strict scientific and regulatory evaluation because non-target species and ecosystem impacts may occur. Complete eradication is generally difficult in large, connected inland waters; therefore, management may focus on population suppression, containment, protection of sensitive habitats, and prevention of further spread. Monitoring before and after control interventions is essential for evaluating effectiveness and identifying unintended ecological effects.

Habitat management and restoration

Maintaining healthy aquatic habitats can improve the resilience of native fish communities and reduce the ecological opportunities available to some invasive species. Habitat management may include restoration of wetlands, riparian vegetation, spawning and nursery habitats, natural flow regimes, and water-quality conditions. Reducing pollution, sedimentation, excessive nutrient loading, and physical habitat degradation can strengthen native fish populations and improve ecosystem functioning. Restoration should be planned according to local ecological conditions because habitat modifications intended to control one invasive species may have unintended effects on native organisms. Combining habitat restoration with invasive-species monitoring and appropriate fisheries management can therefore provide a more sustainable approach than relying only on direct removal.

Sustainable fish production and invasive species management

Sustainable fish production requires a balance between increasing fisheries productivity and maintaining the ecological integrity of inland aquatic ecosystems. Management of invasive fish species should therefore focus not only on reducing their abundance but also on protecting native fish populations, maintaining habitat quality, and preventing further introductions. In systems where invasive fishes have already become established, their controlled utilization may be considered where ecologically appropriate and supported by scientific assessment. At the same time, responsible stocking, species selection, biosecurity, regular monitoring, and ecosystem-based fisheries management are essential to minimize future invasion risks. Integration of fisheries production objectives with biodiversity conservation can help maintain long-term productivity and resilience of inland water resources (Ross *et al*., 2008).

Balancing fish production and biodiversity conservation

Invasive fish management should recognize that high fish biomass does not necessarily represent healthy or sustainable fisheries production. Some invasive species may contribute to fish catches and provide short-term economic benefits, while their long-term effects on native biodiversity and ecosystem functioning may remain a concern. Management decisions should therefore consider species composition, catch trends, ecological interactions, habitat conditions, and socioeconomic value together. Protecting native fish diversity while maintaining productive fisheries requires ecosystem-based approaches that identify vulnerable species and habitats and regulate activities

that promote further spread. Such balanced management can help maintain both ecological integrity and sustainable fisheries production.

Responsible stocking and species selection

Responsible stocking is essential for preventing the introduction and spread of potentially invasive fishes. Species selection should consider environmental suitability, ecological risk, reproductive potential, feeding behaviour, disease risks, and the possibility of escape into natural waters. Stocking programmes should use appropriate sources of seed, maintain accurate records of species movement, and avoid unauthorized introduction of non-native fishes into open water bodies. In aquaculture systems, containment measures should be strengthened to minimize escape during routine operations, floods, and extreme weather events. Risk-based species selection and improved biosecurity can therefore support fish production while reducing potential impacts on native aquatic ecosystems.

Integrated fisheries management

Integrated fisheries management combines invasive-species control with habitat conservation, sustainable fishing, aquaculture biosecurity, biodiversity protection, and community participation. Effective programmes should use information from fish surveys, catch statistics, environmental monitoring, GIS, eDNA, and other modern technologies to identify changes in invasive populations and ecosystem conditions (Larson *et al*., 2020). Coordination among fisheries departments, research institutions, aquaculture producers, fishers, and local communities can improve implementation and monitoring. Adaptive management, in which strategies are regularly evaluated and modified according to monitoring results, is particularly important because invasive species and environmental conditions can change over time. Such integrated approaches can strengthen the resilience of inland fisheries and support sustainable fish production while minimizing ecological risks.

Conclusion

Invasive fish species pose important challenges to the biodiversity, ecological functioning, and sustainable management of inland fisheries. Their introduction, establishment, and spread are influenced by aquaculture activities, fish stocking, ornamental fish trade, hydrological connectivity, environmental changes, and species-specific biological characteristics. Effective management therefore requires an integrated strategy based on prevention, biosecurity, early detection, regular monitoring, targeted control, habitat restoration, and community participation. Modern approaches such as environmental DNA, GIS, molecular tools, and digital monitoring can further strengthen surveillance and management decisions. At the same time, sustainable utilization of established invasive fishes may provide economic opportunities when supported by appropriate safeguards to prevent further spread. Balancing fisheries production with native biodiversity conservation is essential for maintaining healthy and productive inland aquatic ecosystems. Integrated, adaptive, and ecosystem-based management can therefore contribute to long-term sustainability and resilience of inland fisheries resources.

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ACADEMIC EPIDEMICS IN AGRICULTURAL SCIENCES WHEN PERSONAL GLORY OVERSHADOWS SCHOLARLY PURPOSE

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Agricultural science derives its enduring value from the knowledge it creates and the lives it improves. Its achievements deserve recognition when they strengthen food security, sustain natural resources, expand scientific understanding and enhance the dignity of farming. India has benefited enormously from the dedication of its agricultural scientists, teachers, extension professionals and institutional leaders. Preserving that inheritance requires periodic reflection on whether the incentives governing academic life continue to serve the purposes for which institutions were established.

The expression “academic epidemics” is used here as a metaphor for habits that can spread through systems of recognition and reward. It does not describe scientists as deficient or question the sincerity of a generation. It invites consideration of circumstances in which visible personal accomplishments receive greater attention than patient scholarship, collective achievement and public benefit. The purpose is constructive: to help professional aspiration and institutional responsibility strengthen one another as India advances towards its development aspirations for 2047.

Three phases of an evolving scientific culture

The development of modern agricultural science in India may be viewed through three overlapping phases: purposeful transformation, institutional expansion and consolidation, and the contemporary era of increasingly measured scholarship. These are interpretative categories, rather than formally established historical periods. Their boundaries differ across disciplines and institutions. Each contains outstanding achievements, difficult choices and lessons for the future; none should be treated as an age of uniform virtue or inadequacy.

Agricultural research did not begin with Dr MS Swaminathan. ICAR was established in 1929, and earlier institutions and scientists had already laid important foundations. His leadership nevertheless became a defining influence in the modern transformation associated with the Green Revolution. It brought scientific discovery into close relationship with national food needs and agricultural development. Recognizing this contribution honours both his stature and the collective foundations on which he and his contemporaries worked.

The proposed sequence therefore concerns changing institutional emphasis, not the beginning or disappearance of scholarship. Scholarship existed throughout all three phases. The present concern is how it is understood, supported and assessed, and whether the means of recognising excellence remain consistent with the responsibilities of publicly supported agricultural research.

Purposeful research and the strength of leadership

The first phase offers a valuable model of research organised around clearly understood problems. Food insecurity gave agricultural improvement an immediate national significance. The value of scientific work could be understood through its contribution to overcoming production constraints and strengthening confidence in the country's agricultural future. Swaminathan's association with the Green Revolution illustrates this connection between scientific leadership and public purpose.

The institutional lesson is that scholarship becomes especially influential when accompanied by leadership capable of organising collective effort. A promising finding requires testing, adaptation, communication and practical support before its benefits become widely available. Scientists, field workers, administrators and farmers contribute different forms of knowledge. Leadership creates the conditions in which these contributions become mutually reinforcing.

Continuity is particularly valuable in agricultural research. Experiments depend on seasons; breeding programmes and resource management studies demand patience. Stable leadership, accompanied by periodic review, can protect worthwhile investigations from repeated changes of direction. Stability should mean continuity of scientific purpose and fair responsibility, rather than an expectation that any individual must remain indefinitely in office.

The lasting lesson from this phase is therefore practical. Institutions benefit when leaders understand their scientific mandates, recognise the capabilities of colleagues and accept responsibility for shared outcomes. Personal distinction then grows naturally from an environment in which others are also enabled to contribute.

Expansion and the consolidation of institutional values

The second phase may be described as a period of expansion and consolidation, sometimes remembered as a peak in institutional confidence. ICAR's network and the agricultural university system provided a broad organizational base for research and education across commodities, disciplines and regions. Their cumulative contribution to national agricultural development is acknowledged in ICAR's institutional account. Calling this a peak expresses a perspective on institutional culture, rather than a measured claim that subsequent scientific performance declined.

An important principle associated with such confidence is respect for expertise relevant to an institution's mandate. The ability to guide research on soils, crops, livestock, fisheries or agricultural engineering requires informed understanding of the problems concerned. Administrative competence becomes more effective when supported by scientific judgement and an appreciation of field realities.

Institutional traditions can preserve this principle even where particular expectations are not explicitly recorded. Nevertheless, recollections of an unwritten professional norm should not be mistaken for proof that every appointment followed it. The useful task is to identify practices worth retaining and express them through transparent, consistent criteria.

Changing personnel policies need not weaken institutional values. With clear succession arrangements, sound documentation and opportunities for younger colleagues, an organization can renew its leadership while preserving accumulated knowledge. Expansion becomes meaningful when new facilities and responsibilities are accompanied by the expertise and resources necessary to fulfill them. Transition from this period started after superannuation of Dr Raj S Paroda from ICAR service.

Scholarship in the age of measurable accomplishment

The twenty-first century has widened opportunities for scientific communication and collaboration. Publications, citation databases, awards and fellowships provide visible evidence of professional activity. These instruments can help recognize valuable contributions and introduce greater consistency into assessment. Many scientists combine distinguished publication records with substantial contributions to agriculture. Recognition and public service are entirely compatible.

The difficulty arises when the indicators used to recognize achievement begin to determine the choice of work itself. A scientist may reasonably give priority to activities that influence promotion, funding or professional security. If assessment favours easily counted outputs, work requiring prolonged field engagement or contributions that are difficult to attribute to one person may become less attractive. This is a matter of institutional design as much as individual preference.

The international discussion on research assessment recognises this concern. The San Francisco Declaration on Research Assessment recommends judging research on its merits and considering contributions beyond journal metrics, including influence on policy and practice. [3] Agricultural sciences have particular reason to adopt such breadth, given their combination of discovery, education and field application.

Calling the contemporary period a scholarship phase should therefore invite a fuller meaning of scholarship. Careful observation, reproducible experimentation, critical interpretation, good teaching and responsible communication all belong within it. A record of accomplishment becomes more informative when it explains what was learned, who benefited and how the work advanced a larger purpose.

Recognition that strengthens collective achievement

The desire for appreciation is natural. Awards can encourage excellence, fellowships can honour sustained contribution, and professional networks can support collaboration. Difficulties emerge only when recognition becomes detached from the work it is intended to celebrate. Institutions can reduce this risk by explaining their criteria and recognising diverse pathways to meaningful achievement.

Professional interaction with senior colleagues and decision makers is often necessary and useful. Equal access to opportunity, however, should not depend on proximity to influential circles. Open calls, documented assessments, appropriate management of conflicts of interest and reasoned selection decisions can strengthen confidence without questioning anyone's motives. Fair procedures also protect those who deceive recognition from avoidable doubts about how it was obtained.

Agricultural achievement is frequently collective. A successful technology may depend on original discovery, repeated testing, technical maintenance, extension support and farmers' adaptations. Assessment should acknowledge these contributions while remaining clear about each person's role. Team recognition need not obscure individual excellence; it can place that excellence within an honest account of how results were achieved.

Professional ambition becomes most productive when institutions reward the strengthening of others. Mentoring younger scientists, sharing reliable data, supporting colleagues and preserving useful research resources should carry visible value. These practices help scientific distinction become a source of institutional strength rather than an isolated personal asset.

Keeping farmers within the research conversation

It would be unfair to suggest that farmers have disappeared from contemporary agricultural research. Many programmes retain strong field connections, and ICAR's vision explicitly expresses commitment to engagement with farmers and other stakeholders. [4] The constructive question is whether that engagement consistently influences research priorities, implementation and evaluation.

Farmers should participate before a proposed solution is finalised. Their experience can reveal constraints involving labour, affordability, timeliness, risk, markets and local conditions that experimental results alone may not capture. Consultation should include different farming situations, particularly those whose needs may be less visible in conventional measures of agricultural success.

For example, a practice that raises yield under experimental conditions may require labour unavailable at the critical time. An advisory may be technically sound but arrive too late to guide an operation. Such cases do not invalidate the science. They demonstrate why practical suitability is part of the research question and why feedback should lead to refinement.

At the same time, farmers' immediate needs cannot be the only test of scientific value. Basic research, long-term observations and investigations into emerging risks may produce benefits only after many years. A balanced programme should sustain these foundations while maintaining a credible route from knowledge creation to practical use. Scientific depth and agricultural relevance should develop together.

Farmer support and investment in research

Governments face legitimate responsibilities to protect agricultural livelihoods against production risks, market uncertainty and other pressures. Assistance to farmers and investment in research serve related but different purposes. Immediate support can address present distress, while research can expand the options available to reduce future vulnerability. Neither responsibility should be dismissed when considering the other.

It would require detailed budgetary evidence to conclude that increased farmer assistance has directly reduced research allocations. Expenditure may fall under different programmes and respond to several policy considerations. Equally, a shortage of research resources cannot by itself establish that decision makers have lost confidence in scientists. Responsible discussion should examine allocations, actual expenditure, purchasing power and the resources available for scientific operations.

The practical priority is sustained support for work that public institutions are uniquely positioned to undertake. Laboratories, experimental farms, germplasm collections, long-term trials and observational networks need dependable maintenance. Funding a new project while leaving its supporting infrastructure uncertain can limit the value of both investments.

Research institutions, in turn, should explain their requirements through convincing programmes and transparent accounts of progress. Evidence of benefits should include learning, capacity and useful knowledge as well as technologies adopted. This approach can strengthen the case for public investment without promising immediate returns from every investigation or treating unavoidable scientific uncertainty as failure.

Staffing for continuity and emerging needs

Concerns about vacant positions and reliance on temporary appointments deserve careful institutional review. Claims about an increasing national vacancy percentage require comparable data across years, categories and organisations. Even without asserting a uniform trend, the importance of maintaining essential scientific and technical capacity is clear. Research responsibilities cannot be fulfilled through sanctioned positions on paper alone.

Project appointments can bring specialised skills, support defined investigations and provide valuable experience to young professionals. Their contribution deserves respect. However, repeated short appointments are a limited basis for responsibilities requiring continuity, such as maintaining long-term experiments, managing collections or preserving institutional data. Appropriate employment arrangements should follow the nature and duration of the work.

Cadre strength should consequently be considered alongside institutional mandates, credible research programmes and essential continuing functions. High-impact themes can help identify the expertise required, including technical and analytical support. Staffing decisions should also protect less visible capabilities whose value becomes apparent only over time. An institution needs both the capacity to pursue new questions and the ability to sustain its scientific foundations.

Funding restrictions, vacancies and temporary staffing should not be described as treatments for academic epidemics. They are resource and employment arrangements with varied causes and consequences. Where incentives need improvement, the appropriate response is better assessment, leadership and accountability, supported by the resources needed for meaningful work.

Theme based programmes and informed coordination

Theme based research offers a useful way to bring separate disciplines together around important agricultural problems. A theme such as improving the reliability of rainfed production could connect crop improvement, soil and water management, weather information, economics and extension. Its value would depend on a shared problem and an integrated plan, rather than the assembly of unrelated activities under a common title.

Before implementation, proposed programmes should undergo serious discussion by relevant scientists, experienced research managers, field professionals and suitable representatives of intended users. Debate can clarify what is already known, where uncertainty remains and which institutions are best equipped to contribute. Critical examination at this stage expresses commitment to success and helps prevent avoidable duplication.

Each programme should specify the problem, scientific questions, expected contributions, resource requirements and arrangements for review. Milestones should allow adjustment when evidence changes. Expert assessment should remain open to original ideas, including proposals from younger scientists and institutions outside established networks. Good review improves promising work without making conformity a condition of support.

Regional coordination can complement disciplinary leadership by addressing problems shared across institutional boundaries. Assigning such responsibilities to Deputy Directors General could help connect national priorities with regional needs, provided roles, authority and accountability are clearly defined. Coordination should facilitate access to expertise and cooperation while allowing institutions sufficient autonomy to perform their scientific responsibilities effectively.

Renewing scholarly purpose towards 2047

The next phase of agricultural science can draw strength from all three preceding phases: the clarity of purpose associated with national transformation, the institutional capacity developed through expansion, and the powerful methods and wider communication available today. Renewal does not require returning to an earlier administrative model. It requires retaining valuable principles while adapting arrangements to present scientific and agricultural realities.

A practical beginning would be to review how institutions select priorities and assess contributions. Publication quality should remain important, alongside reproducibility, teaching, mentoring, field relevance and the maintenance of essential scientific resources. Assessment should reflect different professional roles and stages of research. A basic scientist, an extension professional and a leader of a long-term field programme should not be judged by an identical checklist.

Leaders can reinforce these changes through everyday decisions. They can protect time for research, encourage informed disagreement, distribute credit fairly and maintain continuity through orderly succession. Periodic reviews should identify achievements and obstacles, including those beyond a team's control. Such arrangements make accountability useful to the people doing the work and credible to those supporting it.

Reform should also learn from practices that have demonstrably worked. Institutions can document successful examples of sustained leadership, effective collaboration and useful farmer participation, then examine the conditions behind their success. Sharing such experience makes professional guidance more convincing. It also gives younger colleagues practical examples to follow, while allowing them the freedom to improve upon what earlier generations have achieved.

For India to realize its development aspirations by 2047, agricultural science must remain intellectually ambitious and socially attentive. The most durable answer to academic epidemics is an environment in which worthwhile work receives patient support and fair recognition. Personal glory then acquires a worthy meaning: the satisfaction of having contributed to knowledge strengthened an institution and helped farming communities face their future with greater confidence.

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WHY DO PRICES RISE IN ONE MARKET BEFORE ANOTHER? UNDERSTANDING AGRICULTURAL PRICE TRANSMISSION

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When onion, potato or pulse prices rise in one market, why does the change not appear immediately in another? And when wholesale prices fall, why might retail prices remain high? These are questions about price transmission: how a price change in one market passes to another. The change may move from a producing region to a consuming centre, from wholesale to retail, or from an international market to domestic markets. It can arrive quickly, slowly, fully, partly—or not at all. Understanding these links helps farmers choose where to sell, traders plan shipments, consumers interpret price changes and policymakers diagnose market disruptions.



Figure 1. How a price signal can travel through agricultural markets.

A price signal on the move

A price change carries information about supply and demand. If heavy rain damages a potato crop in a major producing region, supply may fall and local prices rise. Traders may respond by bringing potatoes from another region. Additional supplies can ease the shortage, linking the prices in the two places. This is spatial price transmission.

Prices also move through a supply chain. A higher price paid to farmers may eventually affect wholesale and retail prices. This is vertical price transmission. The process takes time because produce must be assembled, transported, stored, processed and sold.

Why does one market move first?

Distance and transport costs matter. The price in a consuming market reflects the producing-market price plus the costs of transport and marketing. Fuel, labour, road quality, tolls, loading, handling and storage all influence the final price. If the gap between markets is smaller than the cost of moving the crop, traders may have little incentive to ship it. Persistent gaps despite profitable trade opportunities deserve closer attention.

Time and information also shape the response. Traders need to learn about prices and shortages, find produce, arrange transport and locate buyers. Weak communication or patchy market information can delay that response. Perishable crops add urgency because they cannot always be stored while traders wait for a better price.

Local conditions may differ. Harvest calendars, crop quality, arrivals and consumer demand are not identical across markets. A price rise in one place may reflect a local shortage while another market has adequate stocks. Price comparisons must therefore match commodity grades, dates and units.

Finally, policy and disruptions can alter market links. Export or import controls, procurement, stock releases, taxes, floods, road closures and fuel-cost shocks may change trade routes or slow shipments. These factors can affect how quickly price information and commodities move between markets. A review by Rapsomanikis et al. (2006) discusses how policies and transaction costs, including weak transport and communication infrastructure, can limit price pass-through in developing-country markets.

When increases travel faster than decreases

Price changes do not always pass through equally in both directions. An upstream price increase may be passed on quickly, while a decrease takes longer to reach the next market. Economists call this asymmetric price transmission. The reverse can also happen.

The familiar phrase “rockets and feathers” describes prices that rise quickly but fall slowly. It is a useful image, not a result that should be assumed. Researchers must test whether the data show a difference in the speed or size of adjustment. Possible explanations include changing transport and storage costs, inventory decisions, uneven access to price information, limited competition or differences in bargaining power. Meyer and von Cramon-Taubadel (2004) review these explanations and the challenges in testing for asymmetry.

A price pattern alone cannot prove its cause. For example, faster retail adjustment to wholesale increases may be consistent with market power, but it could also reflect costs, inventories or timing. Researchers need additional evidence before attributing the pattern to a particular actor or practice.

What econometrics adds

A chart of two price series can show whether they appear to move together. Econometric time-series methods go further: they can test whether markets share a long-run relationship, measure how quickly they respond after a shock and examine whether increases and decreases pass through differently.

Table 1. Questions and common econometric approaches

Question	What is examined	Common approaches
Do prices move together over time?	A shared long-run relationship between markets.	Cointegration tests
How does a market respond to a shock?	Direction and speed of short-run adjustment.	Error-correction models, including VECM
Do increases and decreases pass through differently?	Differences in adjustment speed or size.	Threshold models and nonlinear ARDL

An illustration from staple-food markets

A 2023 study of maize, beans and matoke markets in Uganda examined price links between wholesale and retail markets and across locations. The authors found connected wholesale and retail prices, and reported that retail prices responded more strongly to wholesale increases than decreases for some market pairs (Waiswa & Yavuz, 2023). The study illustrates that markets can be connected while price changes still travel at different speeds or magnitudes. The authors discussed information gaps, adjustment costs, inventory management and retailer market power as possible explanations; the pattern itself does not establish which explanation is decisive.

What this means for farmers and consumers

For farmers, better price information helps when deciding where and when to sell, but the highest quoted price is not always the best net return. Transport, handling, commissions, quality requirements and spoilage risk must also be considered. For consumers, the difference between a farm-gate and retail price may cover collection, transport, storage, processing and retailing. A wide price spread alone does not prove excessive margins; researchers need evidence on costs, competition and market conduct.

For policymakers, price-transmission evidence can identify weak market links and inform investment in transport or market information. Monitoring can also help during sharp price changes. The response should fit the cause: a transport bottleneck calls for a different measure than a production shortfall or a competition problem.

A useful signal, not a complete explanation

When prices rise in one market before another, the delay may reflect ordinary costs and the time needed to move produce. It may also point to information gaps, disrupted trade or weak competition. Econometric analysis can measure the connection, the adjustment time and whether rises and falls pass through differently. To explain why a particular market responds first, researchers should combine price data with evidence on trade flows, transport costs, arrivals, policies and market behaviour.

The practical lesson is simple: prices are connected, but they do not move in perfect step. Agricultural econometrics helps us measure how those connections work and where they may be breaking down.

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ANIMAL WELFARE: THE FIVE FREEDOMS

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Introduction

The relationship between animals and human civilization is ancient, deep and mutually dependent. In Indian culture, the cow has traditionally been regarded as a mother, while the bull has been considered a symbol of duty and righteousness. In agriculture, dairy production, transportation, security, research and companionship, animals have played an invaluable role. Indian traditions have generally regarded animals not merely as objects of utility but as an integral part of life, with emphasis on compassion, kindness and protection.

With the rapid development of modern animal husbandry and animal-based industries, productivity has increased; however, challenges related to animal welfare have also increased. Intensive farming systems, limited space, improper nutrition, excessive milking and stressful transportation can adversely affect the physical and mental well-being of animals. Therefore, animal welfare is not only an ethical responsibility but also a scientific and social necessity.

Animal welfare does not simply mean keeping animals alive. It means providing conditions in which animals are free from hunger, thirst, pain, fear and distress and are able to express their natural behaviour. Animal welfare is directly linked with animal health, productivity, reproductive performance and human health under the One Health concept. Research has demonstrated that animals experiencing better welfare tend to have higher productivity, lower disease risk and better-quality animal products.

At the international level, the concept of the Five Freedoms was developed to provide a scientific basis for animal welfare and has been adopted by several international organizations, including the World Organisation for Animal Health. These principles address not only the physical health of animals but also their mental and behavioural well-being. In India, animal welfare also receives legal protection through the Prevention of Cruelty to Animals Act, 1960, and associated rules.

Thus, the Five Freedoms provide practical guidance for livestock keepers, veterinarians, policymakers, researchers and the general public. Their implementation can contribute to sustainable livestock production, food security and human well-being.

The five freedoms of animal welfare

1. Freedom from hunger and thirst

This principle is particularly important in Indian livestock production systems, where animals in many regions may depend on inadequate, imbalanced or seasonal feed resources. Every animal should receive a balanced diet according to its species, age and production level, along with continuous access to clean and adequate drinking water. Programmes related to dairy development and fodder development aim to strengthen this aspect of animal welfare.

2. Freedom from discomfort

Traditional animal housing systems in India are often adapted to local climatic conditions; however, welfare can be compromised when appropriate housing conditions are not maintained. Animals should have:

- Adequate ventilation with a dry and clean environment.
- Protection from heat, cold and rain.
- Sufficient space for standing, sitting and resting.

In dairy animals, particularly, inadequate housing can contribute to heat stress and production losses.

3. Freedom from pain, injury and disease

Although veterinary services have expanded in India, timely treatment remains a challenge in many rural areas. This freedom includes:

- Regular vaccination and deworming.
- Timely disease diagnosis and treatment.
- Appropriate pain management during surgical procedures.
- Special care of injured and sick animals.

National animal disease-control programmes and related initiatives play an important role in this direction.

4. Freedom to express normal behaviour

Traditional Indian livestock systems have often provided animals with opportunities for movement and social interaction. However, these opportunities may become restricted under intensive production systems. Animals should have adequate space for movement and opportunities for appropriate social interaction with other animals. Prolonged tethering and excessive overcrowding are contrary to good animal welfare.

5. Freedom from fear and distress

In the Indian context, animal transportation, handling in markets and slaughter practices are directly associated with this principle. Animals should be protected from overcrowding, hunger and thirst during transportation and should be handled humanely. Cruel handling should be avoided, and scientifically appropriate slaughter practices should be followed. This is important not only for animal welfare but also for food safety and human health.

Role of veterinarians in animal welfare

Veterinarians have a crucial role in implementing animal welfare principles because they are direct guardians of the physical, mental and behavioural health of animals. They contribute through disease prevention, timely diagnosis and treatment, vaccination and the use of humane and scientific approaches during surgical procedures. These practices help reduce pain, fear and unnecessary suffering.

Veterinarians also guide livestock owners regarding balanced nutrition, appropriate housing, hygiene, management practices and animal welfare legislation. Under the One Health approach, veterinarians contribute not only to animal welfare but also to public health and food safety.

Animal welfare and ethics

Animal welfare and ethics are deeply interconnected because animals are sentient beings capable of experiencing pain, fear and distress. From an ethical perspective, humans have a responsibility to treat animals under their care with compassion, respect and humane behaviour. In the Indian context, the principles of non-violence, kindness and coexistence provide an important ethical foundation for animal welfare.

Animals should not be viewed merely as instruments of production; their well-being and quality of life should also be considered. Following animal welfare principles protects their physical and mental health while promoting compassion, responsibility and sustainable development within human society.

Conclusion

In the Indian context, animal welfare represents a combination of legal principles, cultural heritage, ethical responsibility and scientific necessity. The Five Freedoms provide practical guidance for livestock owners, veterinarians, policymakers and society as a whole. By implementing these principles in practice, we can improve the quality of animal life while also contributing to a compassionate, healthy and sustainable society.

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AQUATIC ECOSYSTEM CONSERVATION FOR SUSTAINABLE FISHERIES

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Introduction

Aquatic ecosystems are among the most productive and biologically diverse components of the Earth. Rivers, lakes, reservoirs, floodplain wetlands, estuaries, mangroves, seagrass beds, coral reefs and coastal waters provide essential habitats, breeding and nursery grounds, and feeding areas for fish and other aquatic organisms, while supporting nutrient cycling, primary production, carbon storage, water purification and food-web regulation. Freshwater ecosystems cover only about 1% of the Earth's surface but support more than 40% of the world's freshwater fish species and provide food and livelihoods to millions of people. According to the Food and Agriculture Organization (FAO), global fisheries and aquaculture production reached a record 235 million tonnes in 2024, including 195 million tonnes of aquatic animals (FAO,2026). Aquaculture production of aquatic animals reached 103 million tonnes, surpassing 100 million tonnes for the first time, while capture fisheries produced approximately 92 million tonnes, including a record 12.3 million tonnes from inland fisheries. Including algae, total aquaculture production reached 141 million tonnes in 2024. However, increasing demand for aquatic foods has intensified pressures from habitat degradation, pollution, overfishing, river fragmentation, wetland loss, invasive species and climate change, which can reduce fish recruitment and ecosystem resilience. Therefore, sustainable fisheries require effective fisheries management alongside the conservation and restoration of aquatic ecosystems. In India, total fish production reached 197.75 lakh tonnes during 2024–25, comprising 151.60 lakh tonnes from inland fisheries and aquaculture and 46.15 lakh tonnes from marine fisheries, with inland fisheries and aquaculture contributing approximately 77% of national production (Ministry of Fisheries, 2026).

Aquatic ecosystems and their importance to fisheries

Aquatic ecosystems are not simply water bodies containing fish; they are complex ecological systems in which water, sediments, nutrients, plants, microorganisms, invertebrates, fish and human activities interact. Fish production and recruitment depend on these ecological interactions and the availability of suitable habitats.

Rivers, streams, lakes and reservoirs

Rivers and streams provide feeding, spawning and migration habitats for numerous fish species. Seasonal variations in water level, flow velocity, sediment transport and connectivity with floodplains influence fish reproduction and recruitment. Many riverine fish species migrate between different habitats during their life cycle. Dams, barrages, excessive water abstraction and channel modification can interfere with migration and reduce access to spawning and nursery habitats. Maintaining environmental flows and hydrological connectivity is therefore an important component of river conservation and freshwater biodiversity management. Lakes and reservoirs support capture fisheries, recreational fisheries and, in many cases, cage and pen aquaculture.

Reservoir fisheries can provide important livelihood opportunities, particularly where natural riverine fisheries have declined (Sugunan *et al*., 2023). However, excessive nutrient loading, sedimentation, aquatic weed proliferation, eutrophication and changes in water-level regimes can alter fish habitats and water quality. Sustainable reservoir fisheries therefore require integration of fisheries management with catchment management, habitat protection and regular water-quality monitoring.

Wetlands and floodplain ecosystems

Wetlands and floodplains are among the most important aquatic habitats for fisheries because they provide feeding, nursery and breeding areas for fish. Seasonal connections between rivers and floodplain wetlands allow fish to move between feeding, spawning and nursery habitats, thereby supporting recruitment and maintaining fish populations. Recent research on fisheries and aquaculture in Indian wetland ecosystems has highlighted their importance for fish production, food security and rural livelihoods. Conservation of these ecosystems should therefore be integrated with fisheries development by maintaining natural hydrological connections, controlling pollution and preventing excessive wetland conversion.

Estuaries and coastal ecosystems

Estuaries are highly productive transition zones between freshwater and marine environments. Mangroves, tidal creeks, mudflats, seagrass beds and coral reefs provide important habitats for juvenile fish, crustaceans and molluscs. Many commercially important species depend on estuarine and coastal habitats during their early life stages. Consequently, mangrove destruction, coastal pollution, excessive sedimentation and unplanned development can negatively affect fisheries even when fishing pressure remains unchanged. Conservation and restoration of these habitats are therefore essential for maintaining coastal biodiversity, fish recruitment and sustainable fisheries.

Major threats to aquatic ecosystems

Aquatic ecosystems are increasingly affected by multiple human and environmental pressures. These threats often interact with each other, reducing habitat quality, disrupting ecological processes and affecting fish production and biodiversity.

Habitat loss, degradation and river fragmentation

Urban expansion, agriculture, infrastructure development, sand mining, dam construction, wetland conversion and river-channel modification can degrade aquatic habitats. Such changes may reduce spawning grounds, nursery habitats, shelter and food availability, ultimately affecting fish recruitment and fisheries productivity. Dams and barrages can also interrupt river connectivity and restrict the movement of migratory fish, while altering sediment and nutrient transport. Maintaining environmental flows, improving fish passage and protecting critical habitats can help reduce these impacts.

Pollution, overfishing and invasive species

Domestic sewage, industrial discharge, agricultural runoff, plastics, pesticides and excess nutrients can deteriorate water quality and aquatic habitats. High nitrogen and phosphorus inputs may promote eutrophication and algal blooms, while decomposition of organic matter can reduce dissolved oxygen and create hypoxic conditions. Excessive fishing pressure can reduce spawning biomass and alter the size and age structure of fish populations. FAO reported that 62.3% of monitored marine fish stocks were within biologically sustainable levels in 2021, highlighting the need for effective fisheries management based on stock status and fishing pressure. Invasive alien

species can further threaten native fish by competing for resources, altering food webs, transmitting diseases and modifying habitats. Prevention, early detection and continuous monitoring are therefore important for their management.

Climate change and changing environmental conditions

Climate change affects aquatic ecosystems through rising water temperatures, altered rainfall, floods, droughts, sea-level rise and ocean warming. Changes in temperature, river discharge and water availability can influence fish growth, reproduction, distribution and recruitment, while marine warming and ocean acidification can affect coastal fisheries and habitats. These impacts may become more severe when ecosystems are already degraded by pollution, habitat loss or excessive fishing. Maintaining healthy and connected aquatic habitats, together with continuous monitoring and adaptive fisheries management, can improve the resilience of aquatic ecosystems and fish populations.

Ecosystem conservation approaches for sustainable fisheries

Habitat protection and restoration

Protecting healthy aquatic habitats is essential for sustainable fisheries. Important habitats such as spawning grounds, nursery areas, floodplain wetlands, mangroves, seagrass beds and coral reefs should be identified and protected while maintaining ecological connectivity. Where degradation has already occurred, restoration measures may include wetland rehabilitation, removal of unnecessary barriers, restoration of riparian vegetation, improvement of water quality and reconnection of rivers with floodplains. Long-term monitoring is necessary to assess restoration outcomes and support adaptive management.

Environmental flow and pollution management

Environmental flows are important for maintaining ecological processes in rivers and connected wetlands. Appropriate seasonal flows support fish migration, spawning, larval transport, floodplain inundation and nutrient exchange. Pollution management should focus on reducing untreated sewage, industrial effluents, agricultural runoff, plastics and other contaminants. Controlling nitrogen and phosphorus inputs can reduce eutrophication and algal blooms, while monitoring dissolved oxygen, nutrients, pH and temperature can help detect ecological deterioration. Integrated catchment management and wastewater treatment are therefore important for protecting fish habitats.

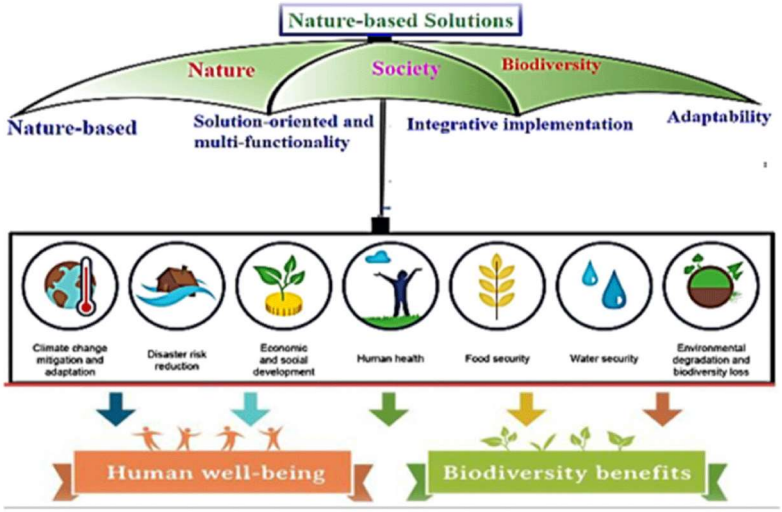


Fig. 1. Conceptual framework for aquatic ecosystem conservation and sustainable fisheries

Sustainable fishing management

Sustainable fishing regulations are necessary to maintain fish populations while allowing continued use of aquatic resources. Measures may include minimum legal-size limits, seasonal closures, gear restrictions, catch limits, protected areas and restrictions on destructive fishing practices. Protection of spawning and nursery grounds can improve recruitment and support fish population recovery. Effective regulations should be based on stock status, fishing pressure and habitat conditions, supported by regular monitoring and participation of fishing communities.

Ecosystem-based fisheries management

A major development in modern fisheries science is the shift from single-species management towards ecosystem-based fisheries management (EBFM). Conventional fisheries management mainly focuses on the population dynamics of individual target species, whereas fish populations are also influenced by predators, prey, habitat conditions, climate, water quality and other human activities (Fortuna *et al*., 2024). Therefore, effective fisheries management requires consideration of the wider ecological processes that influence fish populations and their habitats. EBFM integrates biological, physical, ecological, economic and social factors within a defined ecosystem. It considers ecosystem productivity, trophic relationships, biodiversity, habitat condition and human activities alongside conventional indicators such as fish abundance, biomass and fishing pressure. Ecosystem-level indicators and reference points can help identify ecological changes and support timely management responses. EBFM is particularly relevant to India, where fisheries are closely linked with agriculture, irrigation, hydropower, aquaculture, urban development and biodiversity conservation. An integrated approach can help maintain fish production while reducing pressures on aquatic ecosystems and supporting the long-term sustainability of fisheries and dependent livelihoods.

Community participation and traditional knowledge

Aquatic ecosystem conservation cannot be achieved through government regulation alone. Local fishing communities depend directly on rivers, wetlands, lakes, reservoirs and coastal ecosystems and can therefore play an important role in conservation and fisheries management. Community-based management can improve compliance with regulations and encourage local stewardship of aquatic resources. Fishers also possess valuable knowledge of seasonal fish movements, spawning areas, fishing grounds, water-level changes and variations in fish abundance. Integrating this traditional ecological knowledge with scientific monitoring can strengthen management decisions and improve understanding of local ecosystems. Participatory approaches may include local monitoring groups, co-management committees, seasonal fishing agreements, habitat protection initiatives and awareness programmes. In India, community participation is particularly important because many inland fisheries are small-scale and closely connected with local livelihoods. A recent FAO review of Indian inland fisheries identified habitat loss, water scarcity, pollution, climate change and invasive species as important threats and emphasized the importance of inland fisheries for food security, livelihoods and ecosystem functions.

Role of aquaculture in ecosystem conservation

Aquaculture can contribute to food security and reduce pressure on some wild fish stocks, but its environmental performance depends strongly on management practices. Poorly managed aquaculture can contribute to nutrient enrichment, organic waste accumulation, disease transmission, habitat modification and the escape of cultured or non-native species. Therefore,

aquaculture development should be planned according to the carrying capacity and ecological characteristics of the surrounding environment. Environmentally responsible aquaculture practices include efficient feed management, appropriate stocking densities, wastewater treatment, biosecurity, disease prevention, water reuse and the use of suitable native or well-adapted species (Madsen *et al*., 2022). Integrated systems such as fish–crop and aquaculture–agriculture systems can also improve resource use efficiency by recycling nutrients and water. Sustainable aquaculture should therefore complement ecosystem conservation rather than increase pressure on natural aquatic habitats.

Conservation monitoring and new technologies

Effective ecosystem conservation requires reliable and continuous information on fish populations, habitat quality and environmental conditions. Regular monitoring helps identify ecological changes, assess habitat conditions and evaluate the effectiveness of conservation measures. Modern technologies can improve the coverage, accuracy and efficiency of aquatic ecosystem monitoring.

Environmental DNA and digital monitoring

Environmental DNA (eDNA) enables the detection of aquatic species from genetic material released into water and is particularly useful for monitoring rare, invasive or difficult-to-capture species. Mobile applications, electronic catch reporting, GPS-based monitoring and digital databases can further improve the collection and management of fisheries information (Ulfah *et al*., 2025). These approaches can provide timely data on species occurrence, catch and fishing effort, supporting more responsive fisheries management.

Remote sensing, GIS and acoustic technologies

Satellite imagery, remote sensing and geographic information systems (GIS) can be used to monitor wetland extent, water bodies, aquatic vegetation, shoreline conditions and habitat degradation over large areas. Hydroacoustic techniques can estimate fish distribution and abundance with relatively limited physical sampling and are useful in lakes, reservoirs and marine environments. Together, these technologies provide spatially extensive information for habitat assessment, fisheries monitoring and restoration planning.

Long-term ecological monitoring and adaptive management

Long-term monitoring programmes integrating fisheries production, fish diversity, water quality, habitat characteristics and climate information can provide a comprehensive understanding of ecosystem change. Continuous datasets are important for detecting emerging environmental pressures and evaluating conservation outcomes. Combining conventional field surveys with eDNA, remote sensing, GIS, acoustic methods and digital fisheries data can strengthen evidence-based and adaptive management of aquatic ecosystems.

Conclusion

Aquatic ecosystem conservation is fundamental to the long-term sustainability of fisheries. Healthy rivers, lakes, reservoirs, wetlands, estuaries, mangroves and coastal habitats provide the ecological foundation for fish reproduction, recruitment, feeding and survival. Increasing pressures from habitat degradation, pollution, overfishing, invasive species and climate change can undermine fisheries productivity if they are not addressed through integrated management. India's fish production reached 197.75 lakh tonnes in 2024–25, including 151.60 lakh tonnes from inland fisheries and aquaculture, further emphasizing the importance of conserving aquatic ecosystems

that support this production. Sustainable fisheries therefore require an integrated approach combining habitat protection and restoration, responsible fishing, environmentally sound aquaculture, scientific monitoring, ecosystem-based management and community participation. Conserving aquatic ecosystems is essential for maintaining fish biodiversity, food security, livelihoods and fisheries productivity for future generations.

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SELECTIVE BREEDING IMPROVEMENTS IN MODERN ORNAMENTAL FISH CULTURE: FROM TRADITIONAL SELECTION TO GENOMIC TECHNOLOGIES

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Introduction

Ornamental fishes are valued worldwide for their attractive colours, unique body shapes, fin structures and behavioural characteristics. The remarkable diversity observed in modern ornamental fishes is mainly the result of centuries of selective breeding, where humans have selected and propagated desirable traits over generations. Earlier, ornamental fish improvement depended mainly on breeder experience and visual selection. However, modern ornamental fish culture is undergoing a major transformation through the integration of genetics, molecular biology, reproductive technologies, artificial intelligence and advanced hatchery practices. These approaches help produce attractive, healthy and commercially valuable ornamental fish varieties with greater precision (Gjedrem, 2016).

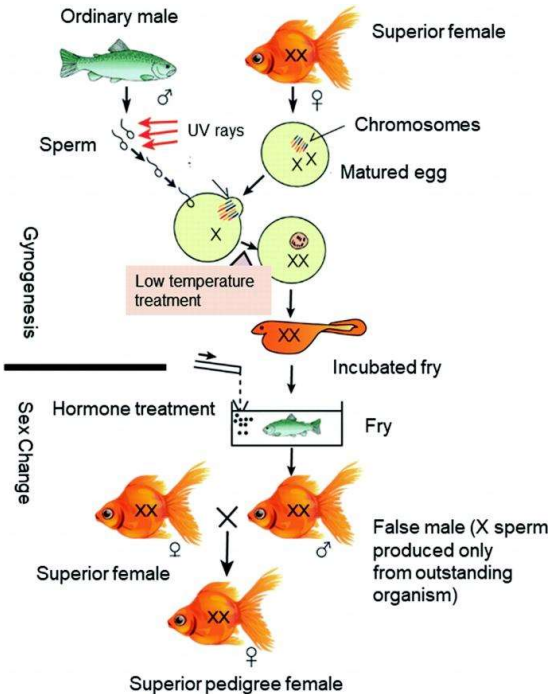


Source: National Fisheries Development Board (NFDB). Ornamental Fisheries of India.

Selective Breeding in Ornamental Fishes:

Selective breeding is the process of choosing fish with desirable inherited characteristics as parents and using them for future generations. The major objectives of selective breeding in ornamental fishes are improvement of colour intensity and patterns, body shape and size, fin development, scale characteristics, growth performance, reproductive ability, disease resistance and adaptation to captive culture conditions. Traditional selective breeding mainly depends on phenotypic selection, where breeders select individuals based on visible characteristics. Although this method has successfully produced many ornamental varieties, it requires several generations and may be influenced by environmental conditions. Modern genetic approaches such as marker-assisted selection and genomic selection improve breeding accuracy by identifying genetically superior individuals with desirable traits (Chen *et al*., 2014; Houston *et al*., 2020).

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Source: Le Verger. et al., (2024). Genomic studies and genetic diversity of domesticated ornamental fish varieties.
(Adapted from literature on genetic improvement and selective breeding in ornamental fishes.)

Examples of Selective Breeding Achievements:

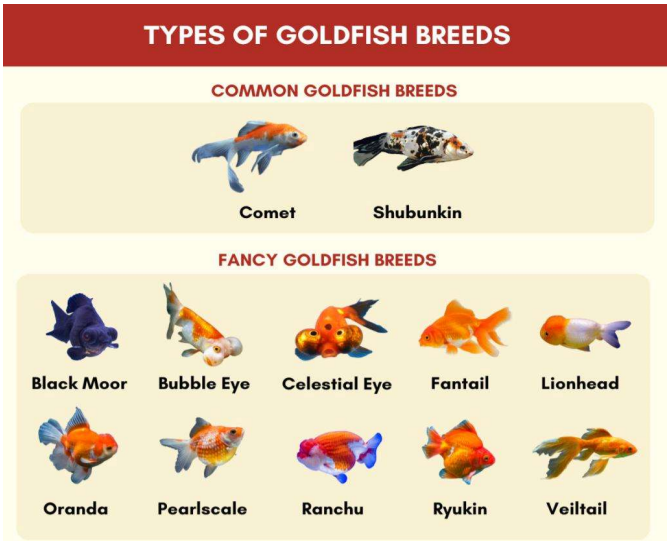
Guppy (*Poecilia reticulata*) is one of the most successful examples of ornamental fish selective breeding because of its short generation time, high reproductive capacity and wide genetic variation. Through repeated selection, numerous varieties such as Full Red, Moscow Blue, Cobra, Tuxedo and Grass guppies have been developed. Breeders select fish with superior pigmentation, attractive body patterns and well-developed fins to produce offspring with desirable ornamental characteristics. Colour variation in guppy is controlled by genes involved in chromatophore development, melanin synthesis and pigment metabolism. Recent molecular studies have improved understanding of these genetic pathways and provide opportunities for future improvement of ornamental strains (Luo *et al.*, 2021).



Source: Judith Betsy, C., Vinisha, M.S. & Smriti, S. Selective Breeding Program in Ornamental Fishes with Special Emphasis on Guppy. Journal of Aquaculture in the Tropics.

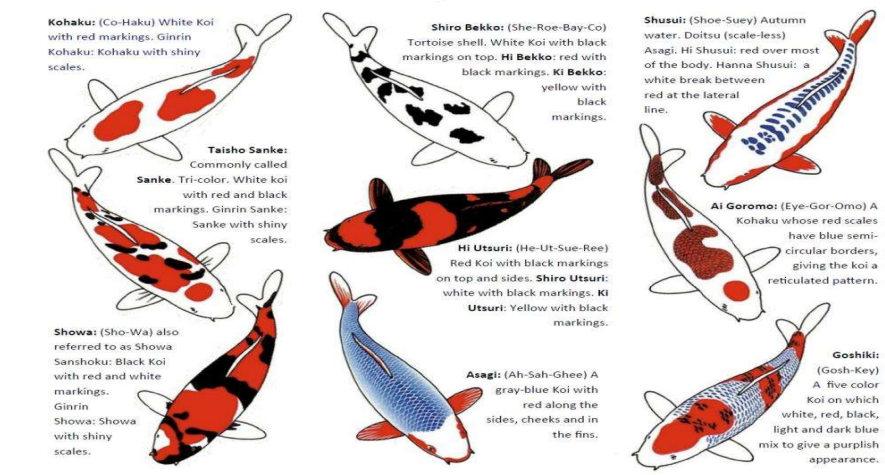
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Goldfish (Carassius auratus) represents one of the oldest examples of artificial selection in ornamental fishes. Long-term selective breeding has resulted in varieties such as Oranda, Ranchu, Lionhead, Telescope Eye, Bubble Eye and Pearl Scale. Selection has modified several traits including body shape, tail structure, eye characteristics, head growth and scale patterns. Recent genomic studies have revealed extensive genetic diversity among domesticated goldfish varieties and have improved understanding of the genetic basis of ornamental traits (Le Verger *et al.*, 2024).



Source: Chapman, F.A. & Miles, R.D.* How Ornamental Fishes Get Their Color. *University of Florida IFAS Extension.

Selective breeding in koi carp (*Cyprinus carpio var. koi*) mainly focuses on colour patterns, skin quality, body form and pattern symmetry. Popular varieties such as Kohaku have been developed through careful selection of colour distribution and stable inheritance of patterns. Genetic studies on pigmentation mechanisms have improved knowledge of colour development and helped in better selection of ornamental carp varieties (Luo *et al.*, 2021).



Source: Chapman, F.A. & Miles, R.D. How Ornamental Fishes Get Their Colour. University of Florida IFAS Extension.

Betta (*Betta splendens*) breeding has produced attractive varieties including Halfmoon, Crown tail, Veiltail and Dragon Scale through selection for fin shape, tail spread, metallic colouration and body patterns. These selective improvements have increased the commercial value and popularity of betta in the aquarium trade.

Selective breeding in discus *(Symphysodon spp.)* has resulted in attractive varieties such as Blue Diamond, Pigeon Blood and Marlboro Red by improving body colour, pattern development and overall appearance. Controlled mating and selection of superior broodstock have helped maintain these commercially valuable strains.

Modern Technologies Behind Selective Breeding Improvements

Modern ornamental fish breeding combines traditional selection methods with advanced scientific technologies. The process begins with identifying superior broodstock possessing desirable traits such as attractive colour, body shape, fin structure, growth and survival. Selected individuals are crossed through controlled mating and line breeding to maintain and improve desirable characteristics over generations (Gjedrem, 2016).

Artificial intelligence and digital imaging technologies are emerging tools for accurate evaluation of ornamental traits. These systems can analyse colour intensity, body symmetry, fin length, scale patterns and pigmentation distribution, thereby reducing errors associated with manual visual selection. AI-based monitoring systems are also being explored for automated health monitoring, behavioural analysis and production management in aquaculture.

Marker-assisted selection (MAS) is a molecular breeding approach that allows identification of DNA markers associated with important traits. By analysing genetic information, breeders can select fish carrying desirable genes even before the traits become visible. In ornamental fishes, molecular studies have identified genetic pathways associated with pigmentation, body shape and scale formation, improving the efficiency of breeding programmes (Chen *et al.*, 2014).

Genomic selection is another advanced approach where thousands of DNA markers distributed throughout the genome are analysed to predict the breeding value of individual fish. This technology allows simultaneous improvement of multiple traits such as colour quality, growth performance, disease resistance and reproductive ability. Although widely applied in food fish breeding, genomic selection is gaining importance in ornamental fish improvement programmes due to its ability to develop stable and genetically superior strains (Houston *et al.*, 2020).

Advanced reproductive technologies such as induced breeding, artificial fertilisation, controlled mating, hormonal manipulation and chromosome manipulation support large-scale production of improved ornamental fish strains. These techniques are useful for developing specific ornamental characteristics and improving production efficiency.

Genome editing technologies such as CRISPR-Cas9 are being explored to understand and modify genes responsible for pigmentation, growth and reproductive traits. Although still under development, these technologies may provide opportunities for precision breeding in ornamental fishes in the future (Houston *et al.*, 2020).

Application of Modern Breeding Technologies in India

India has rich ornamental fish diversity, and the sector is gradually shifting from traditional breeding to scientific production methods. Selective breeding is mainly applied in commercially important

species such as guppy, goldfish, koi carp, betta and discus to improve colour, body shape and fin development. Molecular techniques and genetic studies help identify desirable traits and support future breeding programmes (Luo *et al.*, 2021). Research institutions and fisheries universities in India are also developing captive breeding techniques to reduce dependence on wild collection.

Government Initiatives Supporting Ornamental Fish Development

The Pradhan Mantri Matsya Sampada Yojana (PMMSY) promotes ornamental fish culture through support for breeding units, rearing facilities, brood banks and farmer training programmes. These initiatives improve availability of quality broodstock, encourage entrepreneurship and strengthen ornamental fish production in India.

Future Prospects

The future of ornamental fish breeding depends on the integration of selective breeding with modern technologies such as molecular markers, genomic selection and artificial intelligence. These approaches can help develop varieties with improved colour, growth, disease resistance and adaptability. However, maintaining genetic diversity is essential to avoid inbreeding problems and ensure sustainable ornamental fish production. (Loh *et al.*, 2022; Le Verger *et al.*, 2024).

Conclusion

Selective breeding has transformed ornamental fishes into highly valuable aquatic organisms with diverse colours, shapes and fin patterns. The combination of traditional breeding knowledge with modern genetic technologies can enhance the development of attractive, healthy and sustainable ornamental fish varieties for domestic and global markets.

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TRANSGENIC VEGETABLES: ENHANCING NUTRITIONAL VALUE FOR HUMAN HEALTH

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Abstract

Vegetables are essential for well-balanced diets. About 3 billion people in the world are malnourished due to imbalanced diets. Vegetables can contribute to the prevention of malnutrition disorders. Genetic engineering enables vegetable breeders to incorporate desired transgenes into elite cultivars, thereby improving their value considerably. Transgenic crops, commonly referred to as genetically modified (GM), crops enable breeders to bring favorable genes, often previously inaccessible, into already elite cultivars, improving their value considerably and offer unique opportunities for controlling insects and other pathogens. Various areas where there is an enormous scope for this technology application in vegetables include improved yield, altered nutrition quality, improved resistance to diseases, pests and herbicides and in food stuffs having therapeutic value. Many vegetable crops have been genetically modified to improve traits such as higher nutritional status or better flavour, and to reduce bitter ness or anti-nutritional factors. Transgenic vegetables can be also used for vaccine delivery.

Keywords: GMOs, Horticulture, Phytochemicals, Phytonutriceuticals, Transgenic Vegetables

Introduction

Vegetables are grown worldwide in almost 200 countries and make up a major portion of the diet of humans in many parts of the world. Vegetables play a significant role in human nutrition, especially as sources of vitamins (C, A, B1, B6, B9, E), minerals, dietary fiber and phytochemicals. Vegetables in the daily diet have been strongly associated with improvement of gastrointestinal health, good vision, and reduced risk of heart disease, stroke, chronic diseases such as diabetes, and some forms of cancer. The consumption and caloric contribution of vegetables to the diet varies widely with geographical region, nationality, local customs, and cuisine. Asia produces and consumes more than 70% of the world's vegetables. Vegetable consumption worldwide is rising, reflecting the consumer's increased income, desire of diversity, and awareness of nutritional benefits.

The consumption and caloric contribution of vegetables to the diet vary widely with geographical region, nationality, local customs, and cuisine. In China, the largest consumer, vegetables make up about 35% Of per-capita food consumption, a much higher share than the world average. India, Bangladesh, Cambodia, Vietnam, Laos, and the Philippines are also high producers and consumers of vegetables.

As worldwide health awareness increases and household income grows, an increasing global demand for vegetables is expected. At the same time, available arable land and a suitable water supply are lessening, so energies should be directed to enhance vegetable productivity and quality. Increasingly, consumers in developed and developing countries are concerned about the quality and

safety of their food as well as the social and the environmental conditions where it is produced. It is expected that the assurance of safe vegetable products Will become increasingly important. Food safety legislation in the European Union and in the United States is introducing increasingly stricter standards. In general, vegetable production suffers from many biotic stresses caused by pathogens, pests, and weeds and requires high amounts of plant protection products per hectare. This chapter provides an overview on the prospects for the production of transgenic vegetables to improve vegetable production, emphasizing its place in integrated pest management.

Transgenic Breeding and Nutritional Value for Human Health

Vitamins and Carotenoids

Vitamin A is a major public health problem in much of the developing world. It is estimated that in developed countries, almost 70% of vitamin A comes from animal sources while 30% is derived from plant-based foods. In contrast, people in developing countries derive about 70% to 80% of vitamin A from plant-based foods. Vegetarians and populations with limited access to animal products depend on provitamin A carotenoids. Vitamin A deficiency affects approximately 25% of the developing world's pre- schoolers. It is associated with blindness, susceptibility to disease and higher mortality rates. It leads to the death of approximately 1 to 3 million children each year. The most famous attempt to combat vitamin A deficiency is the development of GM "Golden Rice" genetically transformed rice genotypes with carotenoid biosynthetic genes to deliver more vitamin-A pre cursors in the diet. Although "Golden Rice" has not yet been commercialized, it has shown the potential for genetic manipulation of carotenoid biosynthesis in crops. One of the most obvious benefits of enhancing ca rotenoid levels is the increase in pigmentation, which can lead to more deeply coloured vegetables that are often preferred by consumers. Thus, increasing levels of carotenoid is doubly beneficial, both in terms of nutrition and aesthetics. There are a range of other approaches to enhance the carotenoid levels in potatoes and other root vegetables have silenced the first step in the beta-epsilon branch of carotenoid biosynthesis, lycopene epsilon cyclase (LCY-e) in potato—a tuber crop that contains low levels of carotenoids. This antisense tuber-specific silencing of the gene results in significant increases in carotenoid levels, with up to 14-fold more β-carotene.

Calcium and Zinc

Vegetables offer consumers a diverse mixture of nutrients that promote human health more beneficially than dietary supplements. However, essential nutrients such as calcium (Ca) could be limiting in plant-based diets. Consequently, genetically engineering vegetables containing increased Ca levels may boost Ca uptake, thereby reducing the incidence of Ca deficiencies such as osteoporosis. In this regard modified carrots to express increased levels of the plant Ca transporter sCAX1. These carrot lines were fertile and displayed no adverse phenotypes. Further mice and human feeding trials demonstrated increased Ca absorption from sCAX1-expressing trans genic carrots compared to controls. This research supports alternative means of biofortifying vegetables with bioavailable Ca. Zinc is also an essential element in human nutrition, as its deficiency severely impairs organ function. It is also important for development of intellectual capacity. In experiments to fortify lettuce with this element, used Agrobacterium-mediated gene delivery of a mouse metallothionein mutant β-cDNA in the lettuce cultivar "Salinas 88". The concentration of zinc in the lettuce transgenic plants increased to 400 µg/g dry weight, which is considerably higher than in wild-type plants.

Phosphorous

Humans and animals also need to consume sufficient dietary phosphorus. Plant seeds usually contain an adequate amount of phosphorus, but most of it is in the form of phytic acid (inositol hexaphosphate) *i.e*.; the storage form of phosphorus—which cannot be digested by non- ruminants such as humans. Humans therefore excrete this excess phosphorus in their waste. Furthermore, phytic acid can act as metal chelator of important minerals such as calcium, magnesium, iron, zinc and can contribute to mineral deficiencies in people. About 20 years ago, re searchers identified the first mutants in plants including corn, rice, wheat, soybean, barley and Arabidopsis that have lower amounts of phytic acid in their seeds and an increased amount of phosphorus. Low-phytic-acid germ- plasm accessions have been identified in lentil and common bean, which extends this potential benefit to vegetable legumes. In addition to improving the phosphorus cycle, low-phytic-acid mutants provide further nutritional benefits, increasing the availability of minerals such as calcium, magnesium, iron, and zinc as these are no longer chelated by phytic acid. However, reducing phytic acid has resulted in a concomitant reduction in seed and plant performance; it compromises germination, emergence, stress tolerance and yield.

Flavonoids

Flavonoids are polyphenols whose dietary intake has the potential to prevent chronic diseases. The introduced heterologous, flavonoid pathway genes—stil- bene synthase, chalcone synthase, chalcone reductase, chalcone isomerase, and flavone synthase—to produce novel flavonoids in tomato fruit. These novel flavonoids- flavones and flavonols-increased threefold, mostly in the Q12 peel, which had higher total antioxidant capacity. These findings add further support to the potential of engineering tomato fruit for accumulation of high levels of beneficial nutrients. Similarly, the poliphenol resveratrol—a stilbenoid—shows cancer chemo-preventative activity and may prevent coronary heart disease and arte riosclerosis.

Organosulphur Compounds: Glucosinolates and Thiosulfides

Several epidemiological studies in Asia, the USA and Europe have suggested that the consumption of vegeta bles from the Brassicaceae family, notably broccoli, re duce the risk of lung, breast, colon, and prostate cancer [43]. The phytochemicals thought to be responsible for these health benefits are the isothiocyanates sulphorap hane and indole-3-carbinol. Sulphoraphane was initially thought to induce phase II enzymes in humans, which act against potentially carcinogenic compounds entering the body through the digestive system. However, it is not clear to what degree the anti-carcinogenic activity of sul- phoraphane is achieved by phase II enzyme induction; it also seems that sulphoraphane can induce apoptosis and cell-cycle arrest in a variety of cell types [44]. While re-search continues into the health-promoting mechanisms of Brassica isothiocyanates, others have developed high- glucosinolate broccoli germplasm that results in plants that produce mainly isothiocyanates, compared with standard broccoli cultivars that also produce nitriles. Chro- mosome segments from a wild ancestor, Brassica villosa, have been introgressed to enhance glucosinolate levels. B. villosa alleles determine whether hydrolysis generates indole-3-carbinol or sulphoraphane. Hence, high glucosinolate broccoli might be suitable for increasing the amount of sulphoraphane in the diet.

Sweet Taste

In attempts to reduce bitterness in lettuce. the cloned the gene for the sweet and taste modifying protein miraculin from the pulp of berries of Rich adelladulcifica, which is a West African shrub. This

gene, with the CaMV 35S promoter, was introduced into the lettuce cultivar “Kaiser” using A. tumefaciens GV2260. Expression of this gene in transgenic plants led to the accumulation of significant concentrations of the sweet enhancing protein. People suffering diabetes may use miraculin, which is active at extremely low concentrations, as a food sweetener. The first successful study conducted to engineer genetically the taste of tomato fruit involved transformation of tomato with the thaumatin gene from the African plant katemfe (Thaumatococcus daniellii). Thaumatin is a sweet-tasting protein. Fruit from T2 transgenic plants tasted sweeter than the control plants, leaving a unique and sweet-specific after taste.

Anti-Nutritional Factors

Another approach to improving the health functionality of vegetable crops is to reduce the concentration of anti- nutritional factors. These are naturally occurring com pounds with inhibitory effects on the nutritive potential of plants. In many cases, anti-nutritional factors are produced in planta for pest control, but have secondary effects on human nutrition. The first transgenic cassava plants became available in the mid-1990s as plants with reduced cyanogenic content, which can benefit resource-poor people in rural Africa where this starchy root crop is the base of their diet. Faba bean (Vicia faba) contains condensed tannins that reduce the value of the inherently high protein levels of the crop. Tannins can be removed by the activity of two genes, zt-1 and zt-2, which are pleiotropic for white-flowered plants.

Constraints for Transgenic Vegetable Breeding

As described consumers could benefit from improved access to more nutritious transgenic vegetables and enhanced food safety through transgenic approaches. However, trans- genic crop technology for horticulture remains still in its infancy for several reasons. Vegetables are considered minor crops. Consequently, fewer resources are allocated to transgenic research of horticultural crops compared to field crops, especially by the multinational private seed corporations. While it is becoming less expensive to create transgenic crops, developing a marketable product and responding to the regulatory requirements remains very costly. Development and regulatory costs can be recouped more readily if the product is grown on an extensive area, which is generally not the case for individual vegetable crops. For this reason, most large multinational seed corporations have abandoned the development of transgenic vegetable crops.

Conclusion

Transgenic cultivars can enhance the nutritional value and health advantages of vegetables, playing a crucial role in ensuring sustainable vegetable production. They can effectively combat challenges like virus infections and pests that are hard to tackle solely through traditional breeding methods. The range of techniques, both transgenic and conventional, utilized to boost the nutritional content and health benefits of vegetable crops is expanding. Molecular methods show significant potential for future enhancements. However, successful outcomes will demand more collaboration across disciplines. In addition to molecular biologists and plant breeders, the involvement of nutritionists, food scientists, and other experts from biomedical fields is essential to fully understand the specific functions of plant compounds. A barrier to the successful use of transgenic techniques might be the acceptance or lack thereof transgenic vegetable crops by the public. Vegetable crops developed through biotechnology will thrive if they can show evident benefits and safety to both farmers and consumers.

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ARTIFICIAL INTELLIGENCE IN ORNAMENTAL FISH CULTURE: THE FUTURE OF AQUACULTURE SMART TECHNOLOGY FOR BETTER FISH HEALTH, MANAGEMENT AND PRODUCTION

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Introduction

Ornamental fish culture is an important and growing sector of aquaculture. Ornamental fishes are mainly cultured for their attractive colour, body shape, swimming behaviour and aesthetic value. Successful ornamental fish culture requires proper water quality, feeding, disease management, breeding and careful handling. Traditional fish farming mainly depends on the experience and continuous observation of farmers. Artificial Intelligence (AI) is emerging as a useful technology for developing smarter and more efficient aquaculture systems. AI can analyse information obtained from cameras, sensors and farm records and support faster management decisions.



Figure 1. AI-based smart monitoring system for ornamental fish culture.

Importance of Ornamental Fish Culture

- Provides income and employment opportunities.
- Supports domestic and international ornamental fish trade.
- Requires careful management of water quality and fish health.
- Attractive colour, body shape and behaviour determine market value.
- Captive breeding helps in the production of desirable ornamental fish varieties.
- Proper feeding and disease prevention are essential for maintaining fish quality.

What is Artificial Intelligence?

Artificial Intelligence is a technology that enables computer systems to analyse information, identify patterns and support decision-making. In aquaculture, AI can work together with cameras for visual data collection, sensors for water-quality and environmental monitoring, IoT for data transfer and

storage, Machine Learning for pattern recognition, and Computer Vision for fish behaviour and image analysis.

Why is AI Needed in Ornamental Fish Culture?

- To monitor fish continuously and detect abnormal behaviour at an early stage.
- To improve feeding accuracy and reduce feed wastage.
- To monitor water-quality changes and support early disease detection.
- To improve fish welfare and survival, reduce unnecessary labour and maintain better production records.

AI-Based Water Quality Monitoring

Water quality is one of the most important factors in ornamental fish culture. Sensors can continuously monitor temperature, pH, dissolved oxygen, turbidity and ammonia. AI can analyse the collected information and identify unusual changes.

AI-Based Monitoring Process: Sensors → Data Collection → AI Analysis → Alert → Corrective Action. This system can help farmers identify water-quality problems before they seriously affect fish health.



Figure 2. Sensor-based monitoring of ornamental fish and aquarium environmental conditions.

AI-Based Fish Behaviour Monitoring

Fish behaviour provides important information about their health and welfare. Cameras and computer-vision systems can observe swimming activity, feeding behaviour, abnormal movement, stress-related behaviour, surface activity and schooling behaviour. A sudden change in normal swimming or feeding behaviour may indicate stress, poor water quality or a health problem. Therefore, AI-based behaviour monitoring can provide an early warning system for ornamental fish farmers.

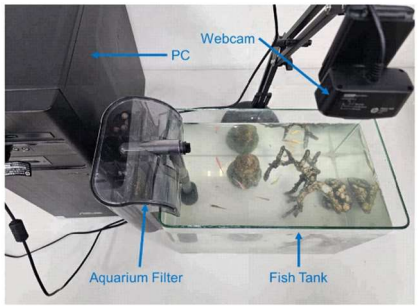


Figure 3. Camera and computer-vision setup for monitoring fish in an aquarium.

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Intelligent Feeding

Feeding is one of the major management activities in ornamental fish culture. Traditional feeding may result in overfeeding, underfeeding, feed wastage, water pollution and uneven growth. AI-based feeding systems can use cameras and fish behaviour to estimate feeding demand. The process is: Camera → Fish Detection → AI Analysis → Feeding Decision → Automatic Feeder. The system can help provide more accurate feeding, reduce feed wastage and maintain better water quality.



Figure 4. Camera-based monitoring system for ornamental fish behaviour.

Benefits: Accurate feeding • Less feed waste • Better growth • Cleaner water.

AI in Disease Detection

Disease is a major problem in ornamental fish culture because diseased fish may lose their colour, appearance and market value. AI-based computer-vision systems can analyse fish images and identify visible abnormalities such as skin lesions, fin damage, abnormal body appearance, colour changes, unusual swimming and external disease symptoms. AI can therefore act as an early warning and screening tool. However, suspected diseases should be confirmed using appropriate professional or laboratory diagnosis.

AI for Fish Identification and Counting

Ornamental fish farms may contain many species, varieties and size groups. AI and computer vision can support species identification, fish counting, size estimation, length measurement, biomass estimation and classification of different fish groups. This can reduce repeated manual handling and make farm monitoring faster (Zhao et al., 2021).

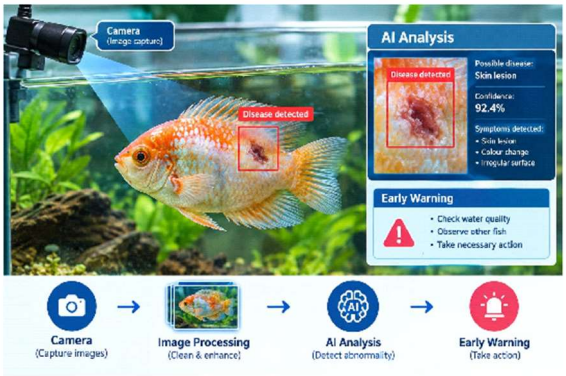


Figure 5. AI-based fish disease detection and early-warning system using computer vision.

AI in Ornamental Fish Breeding

AI can support breeding management by analysing information related to growth, body shape, colour, swimming behaviour, parent performance and reproductive records. In the future, AI can be combined with genetic information and selective breeding programmes to support the production of ornamental fish with desirable characteristics.

AI and Fish Welfare

Continuous monitoring through cameras and sensors can help identify changes in fish behaviour that may indicate stress. Farmers can use AI-based information to check: Water Quality → Feeding → Stocking Density → Disease → Handling Stress. Early detection of abnormal behaviour can help farmers take corrective action and maintain a healthier culture environment.

AI-Powered Larval Stage Identification: An Aquaculture Example

Artificial Intelligence is not limited to ornamental fish culture. The same technology can also be applied to aquaculture hatchery management, particularly for the identification and counting of shrimp larvae. Manual identification of larval stages can be time-consuming and may involve human error. An AI-powered system can help identify and quantify different larval stages automatically.

Major Shrimp Larval Stages

The AI system shown in the provided material identifies: Nauplii → Zoea → Mysis → Post-Larvae. These stages can be identified from microscopic images using machine-learning and computer-vision techniques.

Methodology of AI-Based Larval Identification

Basic workflow: Data Collection → Image Pre-processing → Machine Learning Model → Stage Identification & Quantification.

- Data Collection – Microscopic images of shrimp larvae are collected.
- Image Pre-processing – The collected images are prepared and processed to make them suitable for AI analysis.
- Machine Learning Model – Machine-learning models such as CNN and YOLO can be used to identify larval stages.
- Stage Identification and Quantification – The trained model detects the larval stage and helps in counting and quantifying the larvae.

Quantification Results

Performance Parameter	Result
mAP@50	97.6%
Precision	93.6%
Recall	96.2%

These results demonstrate the potential of AI-based image analysis for automated larval identification and counting.

Innovativeness of AI-Based Larval Identification

- Automated larval stage classification and identification of Nauplii, Zoea, Mysis and Post-Larvae.
- High detection and counting accuracy, reduced human error and reduced labour-intensive manual monitoring.
- User-friendly and scalable technology with real-time monitoring and decision support.

Relevance and Field Application

- Shrimp hatcheries • Aquaculture farms • Research laboratories • Larval production units • Aquaculture monitoring systems.

It can reduce the difficulties associated with manual monitoring and provide faster information for hatchery management. The approach can also be scaled for wider aquaculture applications.

AI-Based Smart Ornamental Fish Farm

A future ornamental fish farm can integrate different AI technologies into one smart system: Sensors + Cameras → IoT System → AI Analysis → Automatic Decision → Farmer Alert. Such a system can support real-time water-quality monitoring, fish behaviour monitoring, intelligent feeding, early disease warning, fish counting, fish identification and production record management.

Benefits of AI in Ornamental Fish Culture

Application	Benefit
Water-quality monitoring	Early warning of water-quality changes
Fish behaviour	Early identification of abnormal behaviour
Intelligent feeding	Better feeding and reduced wastage
Disease detection	Early screening of visible abnormalities
Fish identification	Faster identification
Fish counting	Reduced manual work
Size estimation	Easier growth monitoring
Breeding	Better breeding record management
Welfare monitoring	Early detection of stress
Farm management	Faster decision-making

Challenges in AI Application

- High initial investment for cameras, sensors and computer systems.
- Requirement for good-quality training data.
- Different fish species have different body shapes, colours and behaviours.
- Poor lighting and water turbidity may affect image quality.
- AI systems require proper training and maintenance.
- Technical knowledge may be required for farmers.
- AI predictions should be verified before important health-management decisions.
- Data management and system maintenance are also important.

Future Opportunities

The future of ornamental fish culture may involve the integration of Artificial Intelligence → Machine Learning → Computer Vision → IoT → Robotics → Smart Aquaculture**.** Future systems may provide real-time fish health monitoring, automated feeding, early disease warning, smart water-quality control, automatic fish counting, individual fish identification, intelligent breeding records, remote farm monitoring and automated decision support. AI can also expand beyond ornamental fish culture into hatchery operations, including the automated identification and quantification of shrimp larval stages.

Conclusion

Artificial Intelligence has the potential to transform ornamental fish culture from traditional observation-based management into a more precise and data-driven system. AI can support water-

quality monitoring, fish behaviour analysis, intelligent feeding, disease detection, fish identification, counting, breeding and welfare monitoring. The application of AI in shrimp larval identification also demonstrates how computer vision and machine learning can reduce manual work and improve the speed and accuracy of aquaculture monitoring. Therefore, the integration of AI, computer vision, sensors, IoT and machine learning can contribute to smarter, more efficient and sustainable aquaculture in the future.

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Key Message

"From Fish Monitoring to Larval Identification, Artificial Intelligence is Moving Aquaculture Towards Smarter sand More Precise Production."

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IMPACT OF CLIMATE CHANGE ON MUSHROOM PRODUCTION: CHALLENGES, OPPORTUNITIES AND ADAPTATION STRATEGIES

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Abstract
Mushrooms are important sources of food, income, medicinal compounds and services. But the production of these is strongly influenced by the environmental conditions including temperature, moisture, humidity and precipitation. Climate change is causing these conditions to change, with rising global temperatures, changing patterns of rainfall and more frequent extreme weather events. These changes can affect mushroom growth, fruiting, yield, quality, pressure of pests and pathogens, substrate availability and production costs. Long-term observational evidence shows significant changes in mushroom fruiting phenology in relation to temperature and precipitation. Adaptation strategies include developing alternative substrates, climate-controlled cultivation, heat-tolerant varieties, better pest and disease management, habitat conservation and use of smart technologies and artificial intelligence. Thus, sustainable mushroom production would require a mix of biological, technological and ecological approaches.

Keywords: Climate change, mushroom production, mushroom fruiting, pathogens, sustainable cultivation

Introduction

Climate change is the change in temperature, rainfall and other climatic patterns over a long period of time and is mainly caused by the increase in greenhouse gas emissions. Changes in temperature, rainfall and evaporation rates are impacting on the growth of fungi and the production of mushrooms. Mushrooms, mainly Basidiomycota and Ascomycota, need certain environmental conditions for mycelial growth and fruiting body formation. Changes in temperature and moisture may interfere with these processes, leading to lower yields, poor quality mushrooms, abnormal fruiting bodies and changes in cap color and shape. These processes can be disturbed by changes in temperature and moisture, causing lower yields, poor quality mushrooms, abnormal fruiting bodies and changes in cap color and shape.Thus, both wild and cultivated fungi are susceptible to climate change. Weather conditions and forest ecosystems are very important for wild mushroom fruiting, so climate changes can strongly affect their availability, production and quality.

Why mushrooms are so sensitive to climate

The temperature, humidity, and air-quality requirements of each species of mushroom vary, with fruiting typically requiring more restrictive conditions than mycelial growth. For instance, Lentinula

edodes fruits at 18–20°C, whereas Agaricus bisporus develops vegetatively at 22–25°C but fruits at 5–17°C. Abnormal pins and malformed caps might result from high temperatures. Since mushrooms contain around 85–90% water, humidity is also crucial; cropping typically requires 80–95% relative humidity. Normal pin development requires appropriate CO_2 levels and ventilation. Increases in temperature, CO2, and erratic rainfall due to climate change can therefore lower mushroom yield and quality and raise cultivation costs.

Projected climate change

Global mean temperature is projected to rise by about 2 °C by 2081–2100 under a middle-of-the-road emissions scenario (SSP2-4.5), and by about 4 °C under the highest-emission scenario. For India the corresponding figures are 2 °C and 4 °C by the end of the century. Rainfall is expected to become more uneven, with heavier downpours and more frequent floods, and drier summers and autumns in many regions.

Impacts on cultivated mushrooms

Substrate supply. Most are saprotrophs grown on hardwood sawdust, cereal straws, corncobs and cottonseed hulls. Drought, fire and heat threaten oak and beech forests and warming is projected to reduce the yields of rice, wheat, maize and cotton in most of the world's major producing countries, which would also reduce the residues they leave behind. Wheat yields in China are expected to decline by 3-10% per 1 °C of warming during the growing season and maize yields by approximately 0.5 t/ha per 1 °C. Only a small share of these residues is used for , so the issue is less the total quantity than the quality and price.

Energy costs. Temperature control is expensive. An Italian button mushroom farm used about 0.22 kWh per kilogram of mushrooms, of which 0.18 kWh went to cooling and only 0.04 kWh to heating . More frequent heatwaves mean more cooling, and higher costs for cold storage and transport after harvest. Higher outside CO_2 would also require more fresh-air exchange in growing rooms.

Pests and diseases. Warmth speeds up the life cycles of mushroom pests. The scuttle fly *Megaselia scalaris* completes development in about 33% fewer hours at 28 °C than at 24 °C (Thomas *et al*., 2016). Green mold (*Trichoderma*), *Mycogone*, and bacteria such as *Ewingella americana* also grow faster in warm, humid conditions, so more crops are lost and post-harvest losses in this perishable commodity rise.

Impacts on wild mushrooms

Wild mushroom yields depend on natural temperature, rainfall, and vegetation, so climate change has mixed effects across regions.

Gains in some places. In warm, wet years in Mediterranean Spain, ectomycorrhizal mushroom yields rose to about 230–300 kg per hectare, compared with a long-term average of about 73 kg.

Losses in others. In Rivers State, Nigeria, warming and declining rainfall over a decade lengthened the fruiting season of wild oyster mushrooms by more than 60 days, yet the fruiting bodies became up to 50% light. Highly valued species are expected to lose habitat:

- **Matsutake** (*Tricholoma matsutake*): highly suitable habitat is projected to nearly vanish in Japan and shift to higher latitudes.
- **Caterpillar fungus** (*Ophiocordyceps sinensis*): more than 90% of suitable habitat lies above 3000 m on the Tibetan Plateau and Himalayan flank. Projected losses are large, with India losing roughly 70% of its habitat under some scenarios.

- **Black truffle** (*Tuber melanosporum*): global production is projected to fall by about 15% by 2100 with prices rising about 36%. Drops of 39% in Europe, 56% in the USA, and 81% in Chile are projected, while cooler regions such as the UK and Germany, and parts of Australia and New Zealand, may become suitable.

Wildfire Burned forests generally produce fewer and fewer kinds of mushrooms for years, and mycorrhizal species may take a decade or more to return. Morels are the exception, often fruiting abundantly in the first year after a moderate fire.

Changing fruiting time

Climate change is changing mushroom fruiting times. A Norwegian study showed that autumn fruiting was about 13 days later, especially in early fruiting species, mostly due to warmer autumn and winter temperatures. This reduced the fruiting season to late autumn. Now later, approximately 5°C decline in temperature may be needed to initiate fruiting. Research in Norway and the UK shows that the effects of climate change on fungi vary by species and region.

Threats to genetic resources

Fungal diversity is a natural resource that climate change can erode. India has about 912 species of Basidiomycetes belonging to 121 genera, some of them endemic, such as the milky mushroom. Deforestation and human interference have already lengthened the list of endangered species, and mycorrhizal mushrooms, which depend on living host trees, are especially vulnerable.

Adaptation strategies

Researchers suggest several lines of response.

1. **Alternative substrates.** Use of sugarcane bagasse, coffee grounds, pine sawdust, and other agricultural wastes can reduce dependence on hardwoods.
2. **Breeding and species choice.** Priorities include button mushroom strains that tolerate 20–22 °C during cropping, high-yielding strains that can fruit at 1200 ppm CO_2 and 75–85% relative humidity, and strains with resistance to pests and diseases. Heat-loving species such as the paddy straw mushroom (*Volvariella volvacea*) are attractive alternatives.
3. **Smarter facilities.** Solar-assisted cooling, sensor-based monitoring, and AI-driven control of temperature, humidity, and irrigation can cut energy and water use .
4. **Integrated pest and disease management.** Early-warning systems and biological control agents can reduce risk in warmer, more humid conditions .
5. **Conservation of wild resources.** Options include collecting and storing germplasm in gene banks, preparing a red list of threatened species, protecting habitat, planting mixed forests, and creating fire breaks around productive mushroom forests.

Conclusion

Climate change will affect mushrooms through many routes: temperature and humidity at fruiting, the price and quality of substrates, energy bills, pests and diseases, shifting habitats, wildfire, and fruiting time. Cultivated mushrooms face mainly economic pressures that better technology and breeding can ease. Wild and prized species face more serious ecological risks, because their host trees, soils, and habitat ranges are shifting. Some regions, such as parts of the Mediterranean and higher-latitude areas, may benefit, but hotter and drier regions will probably lose. Most evidence so far comes from small regional studies, and long-term monitoring of farms and wild ecosystems is needed to quantify the changes with confidence.

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BIO-BASED BUSINESS MODELS AND IMPACT ON RURAL ECONOMY

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Abstract

According to the European Commission, the bioeconomy can act as a catalyst for systemic change, tackling economic, environmental and social aspects at once (EC 2020). The transition from fossil-based to bio-based systems represents a paradigm shift in how we produce and consume energy, chemicals, and materials. This evolution is driven by the need to mitigate climate change and reduce reliance on finite, carbon-intensive resources. Fossil-based systems rely on non-renewable underground carbon (petroleum, coal, gas). Fossil-based systems follows linear economies whereas bio-based systems utilize renewable biological resources (crops, wood, algae, waste) that is called circular bioeconomies that reuse and regenerate resources. The bioeconomy is an appealing approach as it holds the promise to uncover new bio-based business models on the basis of regionally available resources, to generate new jobs and economic growth. These ventures typically utilize local skills, resources and labour to provide products and services, acting as a bridge between rural producers and urban markets.

Key words: Bioeconomy, Rural, Sustainable, Growth, Income

Introduction

Bioeconomy interpreted as a component of sustainable development, and as a spatial planning concept. Bioeconomy has the potential to contribute to climate and environmental protection through the efficient and environmentally friendly use of resources. In a rural context, the bioeconomy is the shift from a fossil fuel dependent model to renewable biological resources. This transition turns traditional farms into "bio-refineries," where agricultural waste is no longer discarded but processed into high-value products like biofuels and bioplastics.

Rural enterprises are shifting from being mere suppliers of raw "waste" (biomass) to becoming high-value processing hubs that drive local economic ownership. This transition turns agricultural residues into energy-dense fuels and industrial materials, ensuring that the value created stays within the community. In India, the GOBARdhan scheme facilitates the transition from fossil to biological energy by converting cattle dung and solid waste into biogas and bio-CNG to meet rural energy demands. The transition from fossil-based to biological inputs facilitates a shift from synthetic fertilizers toward bio-fertilizers and bio-pesticides that actively restore soil health. Local ownership ensures that rural populations control their energy supply and retain profits.

Bioeconomy business models drive regional resilience and sustainability:

The survival and growth of rural communities depend heavily on their economic models. Historically, rural economies relied on exporting raw resources, leaving them vulnerable to fluctuating global commodity prices, climate disruptions, and youth out-migration. Transitioning to a modern bioeconomy changes this dynamic. By adopting innovative business models, rural enterprises stop

serving as mere suppliers of raw biomass. Instead, they become centers of high-value manufacturing, turning biological resources into sustainable economic stability for the entire region.

Traditional Model:
(Raw Biomass) → (Exported) ⟶ Urban Centres (Value Added Elsewhere)

Bioeconomy Model:
(Raw Biomass) → (Processed Locally)⟶ High-Value Products + Local Wealth

Local Ownership and Economic Model Typologies:
Local ownership ensures that rural populations control their energy supply and retain profits. Key models that help in achieving this include:

- **Farmer Cooperatives**: Groups that aggregate waste to ensure a steady supply for processing plants, giving them collective bargaining power.
- **Community-Owned Projects**: Decentralized power plants provide lighting and water pumping directly to the village, managed by locals.
- **Small-Scale Entrepreneurship**: Local business owners operating processing units with support from institutions like NABARD in India.
- **Rural Aggregators**: Businesses that bridge the gap between small landholders and industrial buyers, simplifying the complex logistics of collection and storage.

Benefits of the Models:

- **Income Diversification**: Farmers earn from waste sales, while rural youth find jobs in collection, transport and plant operation.
- **Energy Independence**: Local processing reduces reliance on expensive, volatile national grids or imported fossil fuels.
- **Waste Valorization**: Turning potential pollutants (like burnt straw) into valuable assets, promoting a circular economy.
- **Resilience**: Community-managed systems ensure power security even during global energy crisis.

Socio-Economic Impact on Rural Communities
The expansion of the bioeconomy fundamentally alters rural socio-economic dynamics:

- **Job Diversification:** Creating high-skilled industrial and laboratory roles alongside farming.
- **Youth Retention:** Stemming urban migration by providing modern, tech-driven career paths.
- **Circular Resilience:** Keeping wealth within the region by processing local waste into high-value products.

Conclusion
This article examines the conceptual, structural and technological boundaries that define rural enterprises operating within the modern bioeconomy. It focuses specifically on the space where traditional land-based sectors—such as agriculture, forestry, and aquaculture—meet advanced biotechnology, digital tools, and circular economic frameworks. The intersection of traditional agriculture and forestry with modern biotechnology represents a paradigm shift in the rural bioeconomy. This convergence blends centuries old land stewardship with molecular, genetic, and digital technologies. The result transforms rural areas from simple suppliers of raw biomass into hubs of high-value bio-manufacturing.

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THE SLIGHTLESS SURVIVOR : *Ophisternon infernale*

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Abstract
The blind swamp eel, *Ophisternon infernale*, is a cave-adapted freshwater teleost endemic to the karstic subterranean systems of the Yucatán Peninsula, Mexico. Its adaptations to permanent darkness include loss of functional eyes, absence of pigmentation, an elongated scaleless body, and enhanced non-visual sensory abilities. The species inhabits flooded limestone caves, cenotes, groundwater passages, and anchialine systems, tolerating hypoxic conditions through facultative air breathing. Its specialized osteology includes a complete basibranchial series and well-developed upper gill arches. Restricted distribution, groundwater pollution, habitat degradation, and overextraction threaten its survival, highlighting the need for habitat protection, monitoring, long-term conservation measures, and awareness.

Keywords: *Ophisternon infernale***,** blind swamp eel, subterranean habitat, cave adaptation, troglobite, conservation.

Introduction

The blind swamp eel (*Ophisternon infernale*) is a specialized freshwater teleost fish belonging to the order Synbranchiformes and family Synbranchidae (Purnomo 2025). This species is endemic to subterranean freshwater systems, particularly limestone cave networks and swampy underground habitats. Due to its permanent adaptation to aphotic environments, the blind swamp eel exhibits distinct morphological and physiological modifications such as complete eye degeneration, absence of body pigmentation, and an elongated, scaleless, eel-like body. The species possesses a reduced gill system and exhibits facultative air-breathing, enabling survival in hypoxic and stagnant waters. Sensory perception in *Ophisternon infernale* is primarily dependent on mechanoreceptors and chemoreceptors, which compensate for the loss of vision and aid in prey detection and navigation. These adaptations reflect evolutionary regression associated with cave-dwelling organisms (Mar-Silva *et al.,* 2022)



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History

Ophisternon infernale was first described in 1938 by the American ichthyologist Carl Leavitt Hubbs, a prominent authority in systematic ichthyology. During its initial description, Hubbs assigned the species to a new genus and named it *Pluto infernalis*, inspired by Pluto, the Roman god of the underworld, reflecting the fish's subterranean habitat. The specific epithet *infernalis* (later corrected to *infernale*) is derived from Latin, meaning "of the underworld" or "hell," emphasizing its cave-dwelling nature and lightless environment.

Subsequent taxonomic revisions, based on comparative morphological characteristics, resulted in the reassignment of the species to the genus *Ophisternon*, and the accepted scientific name became *Ophisternon infernale*. The genus name *Ophisternon* is derived from Greek, where ophis means "snake" and sternon means "chest" or "breast," referring to the elongated, serpentine body form and ventral anatomical features typical of synbranchid eels.

Commonly referred to as a blind swamp eel, O*phisternon infernale* is characterized by an extremely elongated, scaleless, worm-like body with a smooth, glossy surface. The species lacks functional eyes and pigmentation, features consistent with long-term adaptation to subterranean and cave environments.

Taxonomic Classification:

Domain	: Eukaryota	Kingdom	: Animalia
Phylum	: Chordata	Class	: Actinopterygii
Order	: Synbranchiformes	Genus	: *Ophisternon*
Species	: *Ophisternon infernale*		

The family synbranchidae comprises 27 species in seven genera. (Jairo *et al.,* 2024)

Distribution

Ophisternon infernale, commonly known as the blind swamp eel, is a highly endemic and geographically restricted teleost fish confined to the karstic freshwater systems of the Yucatán Peninsula in southeastern Mexico. The species' known distribution lies within the geographic coordinates approximately 20-21° N latitude and 88-90° W longitude on the peninsula's carbonate platform. (Medina *et al.,* 2001).

This cave-adapted eel inhabits subterranean aquifers, flooded limestone caves, sinkholes (cenotes), and groundwater-filled passages formed by dissolution of the Yucatán's extensive limestone bedrock. It occurs in both dry caves with submerged waters and anchialine systems; coastal caves where fresh groundwater overlies saline water; as well as inland cenotes not directly connected to the sea, particularly along the Caribbean coast and interior lowland of Quintana Roo and Northern Yucatán states. *Ophisternon infernale* is often found coexisting with other cave-adapted species, such as the Mexican blind brotula (*Typhliasina pearsei*), and occasionally, with typical non-troglobitic cave fishes like the catfish *Rhamdia guatemalensis.*

Characteristics

Identification

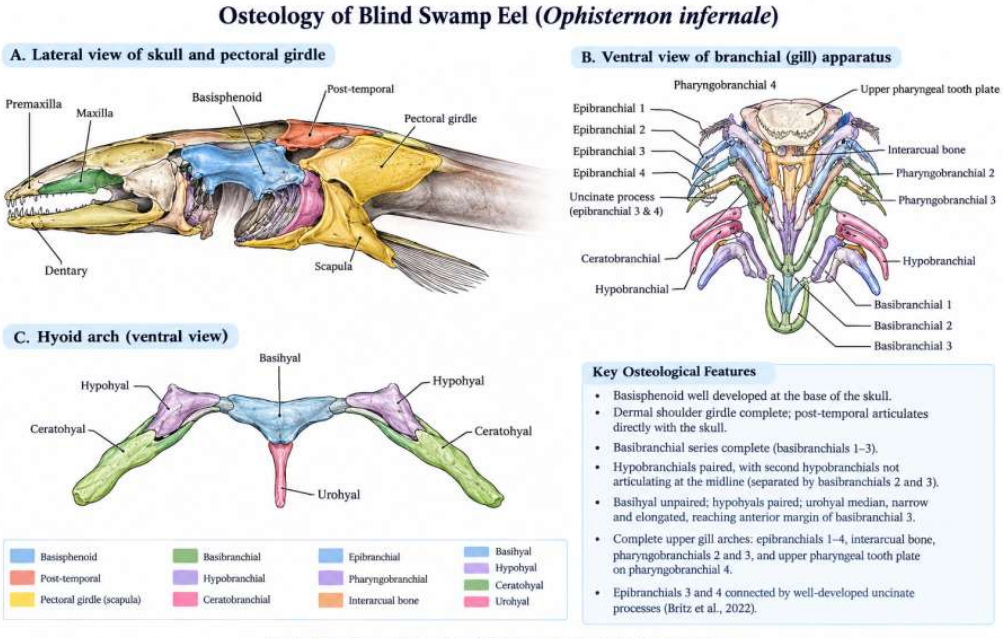
They lack complete melanin pigment and lack of external eyes (Mar-Silva *et al.,* 2022). They have a long head and bulb shaped with sensitive pore Muzzle spatulate is found. They have a standard length of up to 325 nm. They lack scales. Compared with other species of the family Synbranchidae,

these species have a relatively long caudal region, comprising 37-54% of the total body length (Medina *et al.,* 2001).

Osteology

The basisphenoid, a bone located at the base of the skull, is well developed in *Ophisternon infernale*. The dermal shoulder girdle is complete, and the post-temporal bone articulates directly with the skull, providing a firm connection between the pectoral girdle and the cranium. The basibranchial series comprises median skeletal elements situated on the floor of the branchial (gill) apparatus, lying between the paired hypobranchials. In *Ophisternon infernale*, the basibranchial series is complete and consists of basibranchials 1 to 3. The hypobranchials are paired ventral elements of each gill arch, located below the ceratobranchials and on either side of the basibranchials along the floor of the pharynx. The second hypobranchials do not articulate with each other at the midline and remain separated by basibranchials 2 and 3.

The basihyal is an unpaired median bone forming the posterior portion of the hyoid arch and supports the tongue and floor of the oral cavity. The hypohyals are paired bones that connect the basihyal to the ceratohyals, forming the anterior part of the hyoid bar. The urohyal is a median, elongated bone extending posteriorly from the basihyal-hypohyal articulation; in *Ophisternon infernale*, it is narrow and elongated, reaching the anterior margin of basibranchial 3, and serves as an important attachment site for branchial and hypaxial muscles. A complete set of upper gill arches is present. These arches include epibranchials 1–4, an interarcual bone, pharyngobranchials 2 and 3, and an upper pharyngeal tooth plate on pharyngobranchial 4. Notably, epibranchials 3 and 4 articulate with each other via well-developed uncinate processes, forming a characteristic connection within the upper branchial skeleton (Britz *et al.,* 2022).



Ophisternon infernale – Skeletal anatomy of skull, branchial apparatus and hyoid arch

Habitat

They are freshwater inhabitants and most troglobites, *Ophisternon infernale* shows typical regressive troglomorphic traits that associate with life in absolute darkness, it includes both the

absence of pigmentation and eyes. So they prefer dark and oligotrophic subterranean waters permanently. They inhabitat in submerged caves or cenotes well (dry caves) and they also burrowed under the sediment, hiding themselves in the tangles of submerged roots and crevices (Mar-Silva *et al.,* 2022). They are found under stones and mostly at 24m in depth. They can tolerate low oxygen levels and are able to absorb oxygen from the atmosphere with their skin (Medina *et al.,* 2001).

Food and Feeding

These eels, although blind and inhabiting a totally dark environment, show up a circadian cycle and have more feeding activity. Mostly they survive on organic rich sediments and get nutrients from those souls. They mostly feed at night time. They prefer oligotrophic caves, since all the species in a dark environment absorb energy from their environment. Cenote pools (natural underground pools of clear water that form in sinkholes in limestone bedrock) are the "feeding hotspots" to the species that live there. But visual predators attack these species as prey in cenote pools. They feed and prefer oligotrophic caves (Chávez-Solís *et al.,* 2020). *Ophisternon infernale* feeds on the troglobitic shrimp *Creaseria morleyi,* also feeding on faeces of bats and swallows. (Medina *et al.,* 2001).

Troglomorphic Organisms

This species is a troglobite because of its constant habitation in darkness. Their physiological, ecological and behavioral specification is given as reduced metabolism, resistance to starvation, doesn't aggregate often and more, more sensitive to vibrating factors, they have photo-negative behaviour, less aggressive, lack eyes and pigmentation (Monalisha *et al.,* 2024). Dissolved oxygen level when reduced to 1.3 mg/l and below *Ophisternon infernale* comes out of water and takes in atmospheric air (Iliffe 1992).

Reproduction

Ophisternon infernale is a dioecious species, with males and females as separate individuals. The species is oviparous, reproducing through the laying of eggs. Fertilization is external, occurring after the female release's eggs and the male releases milt into the surrounding water. Reproductive behavior in *Ophisternon infernale* includes a notable degree of parental care, which is characteristic of several synbranchid eels. Males are reported to construct or occupy nests or burrows within submerged cave substrates, sediment, or crevices in the limestone environment. After spawning, the male guards and protects the eggs, defending them against potential predators and disturbances. Eggs are typically deposited in protected cavities or burrows, which help maintain favorable conditions such as reduced water flow, stable temperature, and adequate oxygen availability in otherwise hypoxic environments. Parental guarding by males likely enhances egg survival and hatching success, compensating for the low population density and limited reproductive opportunities typical of cave-dwelling fishes.

Threats

Ophisternon infernale faces several significant threats primarily due to its highly restricted distribution, specialized habitat requirements, and small population size. The most critical threat to this species is groundwater pollution, which directly degrades the quality of its subterranean habitat (Medina *et al.,* 2001). Habitat degradation caused by urbanization, tourism development, limestone quarrying, excavation, and construction activities poses another major threat. These activities can alter groundwater flow patterns, damage cave structures, and destroy breeding and refuge sites essential for the species. Additionally, overextraction of groundwater for domestic, agricultural, and industrial use leads to declining water levels in aquifers and cenotes, further reducing suitable

habitat. Environmental pollution, combined with hypoxic conditions, can significantly affect reproductive success, egg survival, and larval development. The species' endemism to a limited geographic area and its occurrence in small, fragmented populations greatly increase its vulnerability to stochastic events and localized disturbances. Limited public awareness and insufficient monitoring of subterranean ecosystems exacerbate the risks faced by this species (Wilkens *et al.,* 2000).

Conservation

Ophisternon infernale has most recently been assessed for The IUCN Red List of Threatened Species in 2018. *Ophisternon infernale i*s listed as Endangered under criteria B2ab (ii,iii) due to its restricted distribution, small population size, and declining habitat quality. The species is primarily threatened by groundwater pollution, including contamination from sewage, garbage, agricultural runoff, excess nitrates, and fecal coliforms, which degrade subterranean aquatic ecosystems. Excessive groundwater extraction for urban, agricultural, and livestock use further reduces suitable habitat and disrupts hydrological stability (IUCN, 2018).

Key conservation measures include protection of cenotes and groundwater habitats, regulation of sewage discharge and groundwater extraction, environmental impact assessments for development projects, and long-term population and water-quality monitoring. Increased research and public awareness are essential for effective conservation of this highly specialized cave-dwelling species (Das, 2020).

Conclusion

Ophisternon infernale is a fascinating species that plays a vital role underground. They are endemic and being in a small population need to conserve them for their better future and increasing biodiversity still more species need to be discovered underground.

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PROMOTING SUSTAINABLE CROP PROTECTION WITH *NEEMASTRA*

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Introduction

Insect-pests remain one of the major constraints to agricultural productivity. Aphids, jassids, whiteflies, mealybugs, leaf-feeding caterpillars and other phytophagous insects can reduce crop growth and yield by removing plant sap, damaging foliage, transmitting diseases, or directly consuming economically important plant parts. Synthetic insecticides have traditionally provided rapid and often effective suppression of these pests. However, their indiscriminate and repeated use has generated concerns regarding pesticide residues, insecticide resistance, effects on pollinators and natural enemies, and contamination of soil and water. This has encouraged renewed interest in botanical pesticides and farmer-prepared bio-inputs. Among these, *Neemastra* occupies a prominent position in Indian natural farming (NF) practices. The term broadly refers to a neem-based fermented botanical preparation used for managing insect- pests. The importance of *Neemastra* extends beyond its insecticidal activity. It represents a philosophy of crop protection in which farmers utilise locally available materials rather than relying entirely on purchased synthetic inputs. Neem, cow dung, cow urine and water are inexpensive and generally accessible on farms practising livestock-integrated NF (Table 1). Consequently, *Neemastra* can be prepared at farm level with relatively little infrastructure.

What is *Neemastra*?

Neemastra is a fermented neem-based botanical pesticide used in NF for the management of insect-pests. The word *Neemastra* is a compound derived from two Sanskrit-derived terms, *viz.* '*Neem*', referring to the neem tree (*Azadirachta indica*), and '*Astra*', meaning weapon or an instrument used for protection or attack. Thus, *Neemastra* literally means 'the weapon of neem' or 'neem-based weapon'. In the agricultural context, the term metaphorically describes neem as a natural weapon against insect-pests. It is particularly associated with the control of sap-sucking insects, including aphids, jassids and whiteflies, as well as small caterpillars.

The formulation is essentially an aqueous extract of neem subjected to fermentation in the presence of cow urine and cow dung. The fermentation period allows biochemical and microbial processes to occur while the neem material remains in contact with the liquid medium. This formulation follows the basic principles of NF, *viz.* locally available inputs, low external dependence, biological activity and minimal reliance on synthetic chemicals.

Table 1. Ingredients used in the preparation of *Neemastra*

Ingredient	Quantity (for one acre land)
Fresh green neem leaves/dried fruits	5 kg
Cow urine	5 L
Fresh cow dung	1 kg
Water	100 L

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This formulation is described by the National Centre for Organic and Natural Farming manual. The NITI Aayog Natural Farming manual provides a proportionally scaled formulation of 10 kg neem, 10 L cow urine, 2 kg cow dung and 200 L water, illustrating that the formulation can be prepared at different scales.

Neem is the key pesticidal component. Neem tissues contain numerous biologically active limonoids and other secondary metabolites. Azadirachtin is among the best-known compounds, and is particularly important for its insect antifeedant and growth-regulating properties. Other neem constituents contribute to repellency and physiological disruption. Interestingly, recent NF technical documentation has reported measurable quantities of phenolics, flavonoids and tannins in *Neemastra*, indicating that the final fermented preparation contains a complex mixture rather than a single active molecule. Cow urine and cow dung serve important supporting roles in the preparation. Cow urine provides a liquid medium and a range of soluble compounds, whereas cow dung contributes microorganisms and organic matter. During fermentation, microbial activity can alter the biochemical environment of the preparation and facilitate the extraction of plant-derived compounds. Thus, *Neemastra* should not simply be viewed as 'neem mixed with water'; it is a fermented botanical formulation in which the ingredients interact over time.

The ingredients are added to a drum containing approximately 200 L of water and thoroughly mixed (Fig. 1). The container is kept under shade and covered with a gunny cloth or similar breathable covering. The mixture is stirred regularly with a wooden stick, 2-3 times a day, to maintain uniformity and facilitate fermentation. After approximately 48 hours, the preparation is filtered through a muslin cloth to remove coarse plant residues.

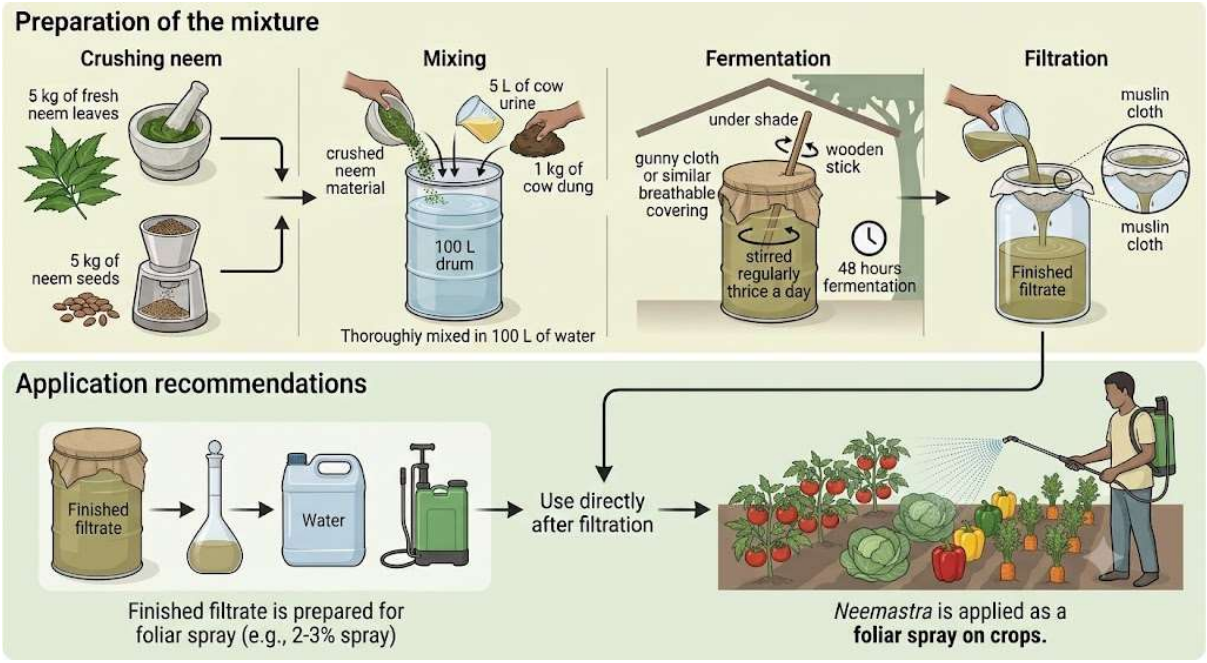


Fig. 1. A scientific flow diagram of the preparation and application of *Neemastra*

Application method and dose

Neemastra is primarily applied as a foliar spray. The filtered preparation should be passed through a fine cloth before loading the sprayer so that suspended plant material does not block the nozzle. It should be used according to the formulation-specific recommendation. Official NF guidance from

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NITI Aayog recommends spraying the 200 L preparation directly on the standing crop after filtration without further dilution. Because formulations vary between manuals, the dose should always correspond to the formulation being prepared. Most of the manuals also describe a 2-3% spray recommendation. Application of *Neemastra* is best timed according to pest incidence rather than following a completely calendar-based schedule. Spraying during cooler parts of the day, particularly morning or late afternoon, can help reduce rapid drying and minimise unnecessary stress to the crop.

How does *Neemastra* work?

Neemastra does not depend on a single mode of action (Fig. 2), rather its effectiveness arises from several interacting mechanisms.

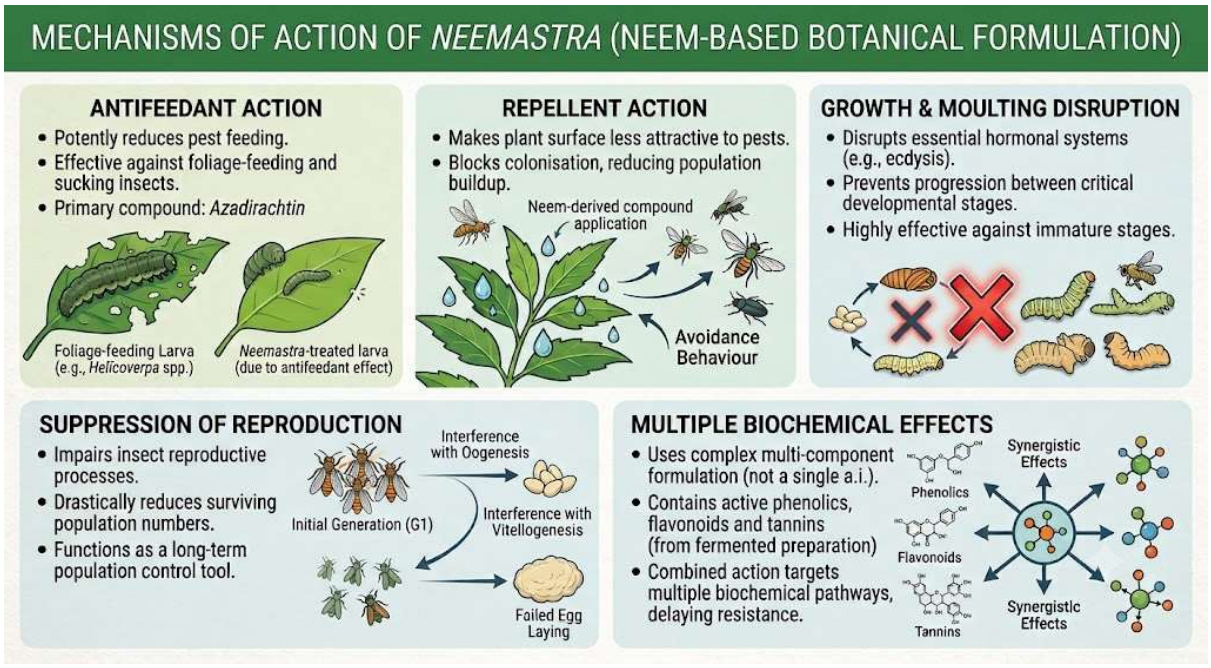


Fig. 2. Mechanism of action of *Neemastra*

Neemastra as an alternative to chemical insecticides

The greatest significance of *Neemastra* lies in its potential to reduce dependence on synthetic insecticides. Unlike conventional insecticides formulated around a specific active ingredient (a.i.) and concentration, *Neemastra* is a farmer-prepared botanical mixture whose insecticidal activity arises from a complex array of natural compounds (Table 2).

Table 2. Fundamental differences between *Neemastra* and synthetic insecticides

Parameter	*Neemastra*	Chemical/Synthetic insecticides
Nature	Botanical, farm-made pest-management preparation	Commercially manufactured chemical pesticide
Principal source	Primarily neem along with cow urine, cow dung and water	Synthetic organic or inorganic a.i. manufactured through chemical processes
Major active ingredients	Neem limonoids such as azadirachtin, salannin, nimbin and related compounds	A specific, chemically characterised a.i. such as imidacloprid, spinosad, λ-cyhalothrin etc.

Parameter	*Neemastra*	Chemical/Synthetic insecticides
Chemical composition	Not standardised; varies with the ingredients, fermentation, temperature and preparation method	Generally standardised and quantified a.i. concentration
Mode of action	Predominantly antifeedant, repellent, oviposition-deterrent and insect-growth-regulating effects; activity depends on formulation	Depends on insecticide class; may include acetylcholinesterase inhibition, sodium-channel modulation, nicotinic acetylcholine receptor disruption etc.
Speed of action	Generally slower	Often faster
Spectrum of activity	Generally more suitable for managing susceptible insect-pests, particularly through behavioural and developmental effects	May range from narrow-spectrum to broad-spectrum depending on the a.i.
Residual activity	Usually relatively short and variable	Often more predictable and, depending on the product, may provide longer residual protection
Effect on non-target organisms	Generally considered comparatively safer when properly prepared and used	Risk varies substantially; broad-spectrum insecticides can adversely affect non-target organisms
Effect on pollinators	Generally lower risk than many broad-spectrum synthetic insecticides, but direct exposure should still be avoided	Some insecticide groups can be highly toxic to bees and other pollinators
Resistance development	Multiple bioactive compounds may potentially reduce selection pressure compared with a single-site insecticide, but resistance is still possible	Repeated use of the same mode of action can strongly select for resistant pest populations
Cost of preparation	Generally low because most ingredients can be locally sourced	Usually higher because of manufacturing, formulation, packaging and distribution costs
Shelf life	Usually short because it is a freshly prepared biological formulation	Usually considerably longer due to formulated and stabilised a.i.s
Persistence in environment	Generally lower persistence of many bioactive neem constituents and greater biodegradability	Highly variable; some compounds degrade rapidly whereas others can persist in soil, water or plant tissues
Compatibility with natural farming	High; specifically aligned with NF principles	Generally inconsistent with systems that prohibit synthetic chemical inputs

a.i. = active ingredient; NF = natural farming

Describing *Neemastra* as a universal one-to-one replacement for all chemical insecticides would be scientifically inappropriate. Its efficacy depends on pest species, pest stage, crop, formulation

quality, environmental conditions and application timing. Severe pest outbreaks may require additional interventions. Natural farming therefore benefits most from integrated pest management (IPM), in which *Neemastra* is one component of a diversified pest-management strategy.

Limitations and precautions

Despite its advantages, *Neemastra* has limitations. Its composition can vary according to neem material, age and quality of ingredients, fermentation conditions and storage. Unlike standardised commercial pesticides, the concentration of active compounds is not necessarily uniform between batches. Its action may also be slower than that of fast-acting synthetic insecticides. Farmers therefore need to monitor pest populations and apply the preparation before they reach economically damaging levels. Proper filtration is essential to prevent sprayer blockage. The preparation should also be kept under appropriate storage conditions. Official guidance indicates that the formulation can be stored for several months under suitable conditions, although quality may vary with storage duration and conditions. Thus, *Neemastra* should be considered a preventive and population-management tool, rather than simply a quick "knock-down" pesticide.

Conclusion

Neemastra represents one of the most accessible examples of how traditional knowledge and contemporary interest in sustainable agriculture can converge to address modern pest-management challenges. Prepared primarily from neem leaves or seed material, cow urine, cow dung and water, this fermented botanical formulation provides farmers with a low-cost and locally producible option for managing important insect pests. Its pesticidal potential is closely associated with the diverse bioactive compounds present in neem, especially azadirachtin, which acts through antifeedant, repellent, growth-regulating and reproductive effects rather than relying solely on rapid toxicity. As concerns surrounding pesticide residues, resistance and environmental sustainability increase, *Neemastra* offers an important avenue for reducing dependence on synthetic insecticides. Nevertheless, its greatest value lies not in replacing every chemical pesticide, but in becoming part of a diversified, preventive and ecologically based pest-management system. When combined with biological control, cultural practices, resistant cultivars and regular pest monitoring, *Neemastra* can strengthen the foundation of NF and contribute to a more self-reliant, economical and environmentally responsible agriculture.

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CLIMATE CHANGE, FISHERIES RESOURCE CHALLENGES AND ADAPTATION STRATEGIES

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Introduction

Climate change is projected to affect ecosystems, societies and economies, increasing pressure on livelihoods and food supplies, including fisheries and aquaculture. There is an urgent need to understand where climate change is likely to reduce livelihood opportunities for fishers and where investment in alternative rural and urban enterprises is required. Climate change can negatively affect food security, while improved agricultural productivity, economic growth and international trade may help mitigate regional food shortages. Aquatic animal foods play a major role in global nutrition, providing at least one-fifth of animal protein consumption for approximately 3.1 billion people worldwide. They also supply high-quality protein, essential amino acids, vitamins, minerals and omega-3 fatty acids (Kumar *et al*., 2023). Fisheries and aquaculture further support more than 600 million livelihoods globally, highlighting their importance for food security, nutrition and socioeconomic well-being. Fish also provides an important source of household income and contributes to local economies and foreign exchange earnings. Fishing is often part of mixed livelihood strategies, particularly where other food production and income-generating activities are insufficient. Coastal and reef-dependent communities are especially vulnerable because many depend heavily on reefs for food, livelihoods and protection from natural disasters. Rising sea temperature is a major cause of coral bleaching and degradation of reef ecosystems, while ocean warming and acidification may further increase coral reef losses (Adeniran *et al*., 2024). Changes in sea temperature and ocean currents can also shift the distribution of marine fish stocks, creating benefits in some areas and losses in others. Therefore, fishers need to reduce dependence on a narrow resource base by utilizing a broader range of species and diversifying their sources of income.

Climate change and aquatic ecosystems

Climate change is altering the physical, chemical and biological characteristics of marine, coastal and freshwater ecosystems. Changes in temperature, precipitation, river discharge, sea level, ocean acidity and the frequency of extreme weather events can influence aquatic habitats, species distribution, productivity and fisheries resources. These changes may affect fish growth, reproduction, recruitment and survival, thereby altering the composition and productivity of aquatic ecosystems.

Rising temperature

Increasing air and water temperatures are among the major consequences of climate change affecting aquatic ecosystems. Fish and other aquatic organisms are highly dependent on environmental temperature because their metabolic activity, growth, reproduction and survival are closely linked to thermal conditions. Rising water temperature can increase metabolic demands and

oxygen requirements, while reducing the availability of dissolved oxygen in water. Consequently, fish may experience thermal stress, changes in feeding and growth, altered reproductive cycles and shifts in their geographical distribution. In marine ecosystems, warming has already contributed to changes in species composition and fisheries productivity in several regions.

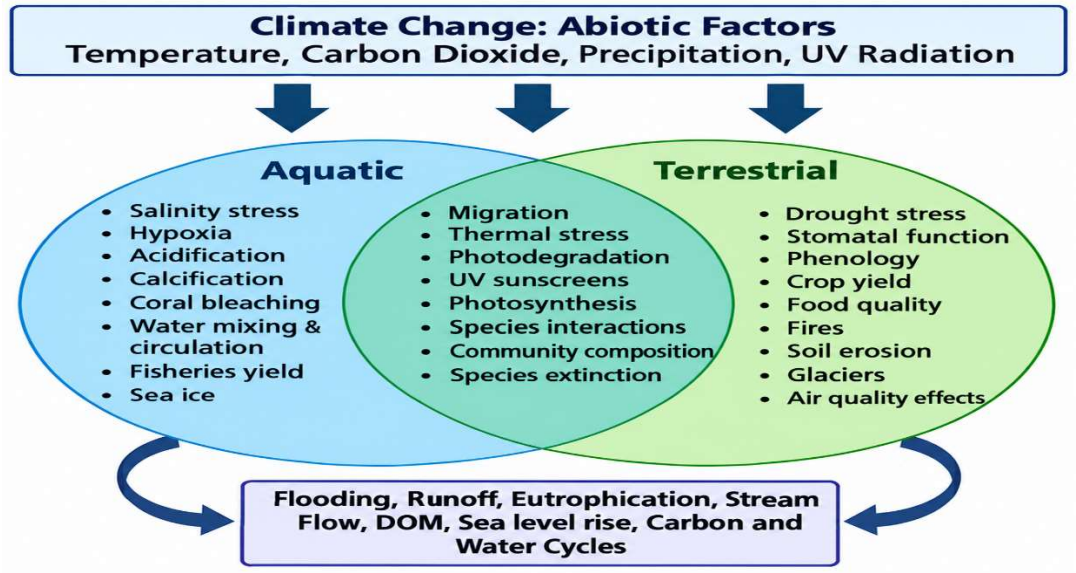


Figure 1. Major effects of climate change–driven abiotic factors on aquatic and terrestrial ecosystems.

Changes in precipitation and river flow

Climate change is modifying rainfall patterns, the timing and intensity of precipitation, and freshwater availability. Changes in precipitation directly influence river discharge, lake levels, floodplain connectivity and the availability of aquatic habitats. Reduced rainfall and prolonged drought can decrease river flow and water availability, whereas intense rainfall may produce floods, increased sediment loads and rapid changes in water quality. Such alterations can affect fish migration, spawning grounds, nursery habitats and food availability. Changes in river flow are therefore particularly important for inland and riverine fisheries, where fish production is strongly associated with seasonal hydrological conditions (Haque *et al*., 2025).

Sea-level rise

Sea-level rise poses important risks to coastal and estuarine ecosystems, including mangroves, wetlands, estuaries and coastal aquaculture areas. Increasing sea levels can cause coastal flooding, shoreline erosion and saltwater intrusion into freshwater systems. Changes in salinity can alter the distribution and abundance of aquatic species according to their tolerance limits. In coastal aquaculture, increased salinity and flooding may affect farm productivity and infrastructure, particularly in low-lying areas. Sea-level rise can also modify coastal habitats that serve as important breeding, nursery and feeding grounds for fish and other aquatic organisms.

Ocean warming and acidification

Ocean warming and acidification are major climate-related changes affecting marine ecosystems. Increased concentrations of atmospheric carbon dioxide lead to greater absorption of CO_2 by seawater, resulting in a decline in ocean pH. Ocean acidification can interfere with calcification and development in many marine organisms, particularly corals and shell-forming organisms. At the

same time, ocean warming can influence species distribution, primary productivity, food-web interactions and fish physiology. The combined effects of warming, acidification and declining oxygen availability can increase stress on marine organisms and fisheries resources.

Climate change-related challenges to fisheries resources

Climate change is creating multiple challenges for fisheries resources by altering environmental conditions, aquatic habitats and ecosystem processes. Changes in temperature, precipitation, ocean circulation and extreme weather events can modify the distribution and abundance of fish populations. Many species are shifting towards cooler waters or changing their seasonal migration patterns, affecting traditional fishing grounds. Changes in temperature and water quality can also influence fish growth, reproductive timing, spawning success and recruitment, ultimately affecting population sustainability. Climate-related pressures, together with habitat degradation in rivers, wetlands, estuaries, mangroves and coastal areas, can further reduce suitable breeding, nursery and feeding habitats. These changes may lead to fluctuations in fisheries productivity and catch, creating greater uncertainty for fishers and fisheries-dependent communities. Reduced and unpredictable catches can affect household income, employment and the availability of fish as an important source of animal protein and nutrients. Therefore, climate change represents an important challenge to the ecological sustainability of fisheries as well as the livelihoods and food security of communities dependent on aquatic resources.

Climate change impacts on aquaculture

Climate change is affecting aquaculture through increasing temperature, changing rainfall patterns, water-quality fluctuations, extreme weather events and changes in disease dynamics. These stressors can influence fish metabolism, growth, survival, reproduction and feed utilization, while also increasing production risks and operational costs. The vulnerability of aquaculture depends on the cultured species, farming system, location, water availability and adaptive capacity of farmers. Therefore, climate-resilient aquaculture requires improved farm management, environmental monitoring, suitable species selection and risk-based planning.

Thermal stress and water quality changes

Rising water temperature can increase metabolic activity and oxygen demand in cultured organisms, while simultaneously reducing dissolved oxygen availability. Prolonged thermal stress may reduce feed intake, growth and survival and can alter reproductive performance. Climate-induced changes in rainfall, evaporation, salinity, turbidity, pH and dissolved oxygen can further affect water quality and farm productivity. Regular monitoring and appropriate management of temperature, dissolved oxygen and other critical water-quality parameters are therefore essential for maintaining suitable culture conditions.

Disease and parasite risks

Climate-related changes in temperature and water quality can modify host–pathogen interactions and may increase the occurrence, transmission and geographical range of some aquatic diseases and parasites. Stress caused by unsuitable environmental conditions can also reduce the resistance of cultured organisms to infection. Consequently, climate change may increase disease-related production losses and create additional biosecurity challenges (Subasinghe *et al*., 2023). Strengthening routine health monitoring, maintaining good water quality, implementing appropriate stocking densities and applying effective biosecurity measures are important components of climate-resilient aquaculture.

Extreme weather events and farm infrastructure

Floods, cyclones, storms, droughts and other extreme events can directly damage ponds, cages, hatcheries, water-supply systems and other aquaculture infrastructure. Flooding may cause stock escape, contamination and deterioration of water quality, whereas drought can reduce water availability and increase water temperature and salinity. Strengthening farm infrastructure, selecting appropriate sites, maintaining emergency preparedness and developing disaster-risk management plans can reduce physical and economic losses.

Feed, seed and production challenges

Climate variability can affect the availability and quality of feed ingredients, seed production and overall farm productivity. Changes in temperature and water quality may alter feed intake and feed conversion, while extreme events can disrupt hatchery operations and seed supply. Such effects can increase production costs and create uncertainty in farm planning. Improving hatchery management, maintaining reliable seed supply, optimizing feeding practices and using locally appropriate production systems can help reduce climate-related production risks.

Adaptation strategies for sustainable fisheries and aquaculture

Adaptation requires a combination of ecosystem-based management, improved farm practices, technological innovation, climate information and effective governance. FAO emphasizes risk-based and flexible approaches that allow fisheries and aquaculture management to respond to changing environmental conditions. Climate adaptation is most effective when actions are supported by continuous monitoring, stakeholder participation and periodic evaluation.

Ecosystem-based fisheries management

Ecosystem-based fisheries management considers climate variability, habitat condition, species interactions and human activities together rather than managing individual fish stocks in isolation. Flexible harvest controls, climate-informed management decisions and sustainable fishing practices can help maintain fish populations under changing environmental conditions. Adaptive management should be periodically revised using updated ecological and climate information.

Habitat protection and restoration

Protection and restoration of mangroves, wetlands, estuaries, seagrass beds, coral reefs and other critical aquatic habitats can strengthen the resilience of fisheries resources. These ecosystems provide feeding, breeding and nursery grounds and support biodiversity and fisheries productivity. Habitat restoration, reduction of pollution and sustainable coastal-zone management can therefore reduce the vulnerability of aquatic ecosystems to climate-related disturbances.

Climate-resilient aquaculture practices

Climate-resilient aquaculture involves modifying farming practices according to local climate risks. Measures include improved water-quality management, efficient water use, appropriate stocking densities, better pond design, farm-level biosecurity and climate-suitable site selection. Regular assessment of climate risks can help farmers identify vulnerable stages of production and implement suitable measures before major losses occur. FAO's recent Aqua-Adapt framework specifically emphasizes risk assessment, adaptation planning, implementation and continuous monitoring and evaluation.

Species and farming-system diversification

Diversification can reduce dependence on a single species or production system and distribute climate-related risks. Selection of species and strains with appropriate tolerance to local

temperature, salinity and other environmental conditions can improve production stability. Integrated systems, including combinations of aquaculture with agriculture or other compatible production activities, can also improve resource use and provide additional sources of income.

Improved early warning and climate information systems

Early warning systems can provide timely information on cyclones, floods, droughts, marine heatwaves, harmful environmental conditions and other climate-related hazards. Linking climate forecasts with farm and fisheries management allows fishers and farmers to take preventive actions, such as adjusting operations, protecting infrastructure or modifying harvesting schedules. Climate monitoring, remote sensing and locally relevant environmental indicators can strengthen decision-making and reduce losses.

Technological and management innovations

Technological innovation can improve the capacity of fisheries and aquaculture systems to respond to climate variability. Remote sensing, geographic information systems, automated water-quality monitoring, improved hatchery technologies and efficient water-management systems can support climate-informed production and resource management. In aquaculture, improved infrastructure, efficient resource use and suitable production technologies can reduce exposure to environmental stress.

Strengthening fisheries governance and community participation

Effective climate adaptation requires coordination among government agencies, researchers, extension services, fishers, aquaculture farmers and local communities. Policies should integrate climate risks into fisheries and aquaculture planning while supporting access to information, finance, infrastructure, insurance and technical assistance. Participation of local communities is particularly important because fishers and farmers possess practical knowledge of local environmental conditions and can contribute to the development and implementation of suitable adaptation measures (Mozumder *et al*., 2023).

Conclusion

Climate change is emerging as a major challenge to the sustainability of fisheries and aquaculture by altering temperature, hydrological conditions, aquatic habitats, species distribution, productivity and disease dynamics. These changes can affect fish growth, reproduction, recruitment, catches, aquaculture production and the livelihoods and food security of fisheries-dependent communities. Strengthening climate adaptation therefore requires an integrated approach involving ecosystem-based fisheries management, habitat protection and restoration, climate-resilient aquaculture practices, species diversification, improved early warning systems and climate-informed technologies. Effective governance, scientific research and active participation of fishers and aquaculture farmers are also essential for implementing locally appropriate adaptation measures. Coordinated and adaptive management can enhance the resilience of fisheries and aquaculture systems and support their long-term sustainability under changing climatic conditions.

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COFFEE BERRY BORER (*Hypothenemus hampei*): A TINY BEETLE, A MAJOR THREAT TO COFFEE PRODUCTION

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Abstract

The coffee berry borer (CBB), *Hypothenemus hampei*, is one of the most economically important insect pests affecting coffee production worldwide. Its concealed feeding and breeding behaviour inside coffee berries makes early detection and effective management particularly challenging. In India, the pest poses an increasing threat to coffee-growing regions, including the high-altitude tribal coffee areas of Andhra Pradesh, where its recent occurrence in the Araku Valley has emphasized the need for strengthened surveillance and timely management. Infestation begins when adult females bore into developing coffee berries and establish galleries leading to direct damage of the coffee bean, resulting in both quantitative and qualitative losses. Because the majority of the insect's life stages remain protected within the berry, management should focus on preventing infestation and reducing sources of reinfestation. An integrated pest management (IPM) strategy involving field sanitation, complete harvesting, removal of fallen and leftover berries, proper post-harvest drying, population monitoring using alcohol-based Broca traps, and biological suppression with *Beauveria bassiana* can substantially contribute to reducing CBB populations.

Introduction

Coffee is an economically important plantation crop cultivated across several tropical regions of the world and serves as a vital source of income for millions of farming households. In India, its cultivation is traditionally concentrated in Karnataka, Kerala and Tamil Nadu, while production has gradually extended to non-traditional areas, including the high-elevation tribal landscapes of Andhra Pradesh. Coffee productivity in these regions is influenced by a range of biotic and abiotic constraints, particularly insect pests, diseases and climate-related stresses. Among the insect pests affecting coffee, the coffee berry borer (CBB), *Hypothenemus hampei*, is considered one of the most serious threats to both yield and bean quality. The pest is particularly difficult to manage because of its distinctive life history. Adult females bore into developing coffee berries and establish galleries within the fruit, where feeding and reproduction take place in close association with the coffee seed. As a result, much of the pest's developmental period occurs within the protected environment of the berry, making early detection difficult and reducing the effectiveness of control measures once infestation is established. Consequently, timely surveillance and management of adult beetles before or during berry penetration are critical for minimizing crop losses (Damon, 2000; Johnson *et al.*, 2020).

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Coffee Berry Borer in India

The coffee berry borer (CBB), *Hypothenemus hampei*, is recognized as a major insect pest of coffee in India and has considerable economic significance in coffee-producing regions. The Coffee Board has included this pest among the key insect constraints requiring an integrated approach for effective management. Its recent occurrence in the Araku Valley of Andhra Pradesh is particularly noteworthy because the region represents an important non-traditional coffee-growing tract.

As reported in the Coffee Board's *India Coffee* magazine, the presence of CBB was detected in Araku Valley during August 2025. Subsequent field investigations confirmed infestation in green coffee berries as well as residual fruits at Pakanakudi village. The detection of this pest presents an emerging concern for coffee cultivation in the region, particularly for tribal farming communities whose livelihoods are closely associated with coffee production. Early recognition of infestations, systematic field monitoring and prompt implementation of recommended management measures are therefore essential. Strengthening plantation sanitation, conducting regular surveillance and ensuring timely dissemination of technical advisories to growers can play an important role in preventing the pest from becoming firmly established and spreading to additional coffee-growing areas.

Identification and appearance

The coffee berry borer, *Hypothenemus hampei*, is a tiny beetle that ranges from dark brown to nearly black in colour. Females are generally larger than males and play the principal role in locating and colonizing coffee berries. A gravid female usually enters a suitable berry through the tip or disc region and subsequently constructs a gallery leading towards the coffee seed. Because of its extremely small body size, the insect is difficult to detect during the initial stages of infestation. One of the earliest external signs is a small, round perforation on the berry surface near the entry region. However, the concealed nature of the pest is its most important biological characteristic. After gaining access to the berry, the insect spends much of its developmental period within the fruit, where eggs, larvae and pupae remain relatively protected from external control interventions. This makes management after successful penetration considerably more difficult (Damon, 2000; Johnson *et al.*, 2020).



Figure 1: Adult coffee berry borer, Hypothenemus hampei

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Symptoms and damage

The first symptom is usually a tiny hole near the tip of the coffee berry. As infestation progresses, additional holes may become visible. Internally, the beetle and its immature stages excavate galleries and feed on the endosperm. The pest therefore affects not only production quantity but also bean quality, making it an important economic pest (Damon, 2000; Johnson *et al*., 2020).



Figure 2: Typical external and internal symptoms associated with coffee berry borer infestation.

Life cycle and population development

The life cycle of CBB is closely associated with the availability of suitable developing coffee berries. Females initiate infestation, lay eggs inside the berry, and the larvae subsequently feed on the coffee seed. Pupation also occurs within the berry. Adults emerging from infested berries can disperse and attack fresh berries. Under favourable conditions, overlapping generations may occur because berries remaining on plants or on the ground provide continuous breeding sites (Damon, 2000; Moreno-Ramirez *et al.,* 2024). This is why post-harvest sanitation is a critical component of CBB management. The cryptic life cycle creates a major challenge - once the insect has penetrated deeply into the berry, conventional external treatments become considerably less effective. Therefore, preventing the pest from entering the berry is more important than attempting to control large populations after infestation has become established.

Integrated pest management of coffee berry borer

Successful management of CBB cannot depend on a single control measure. An integrated pest management (IPM) approach combining cultural, mechanical, biological and monitoring-based measures is more appropriate (Aristizabal *et al.,* 2016; Aristizabal *et al.,* 2017; Johnson *et al.,* 2020).

1. Field Sanitation: Timely and complete harvesting is the foundation of CBB management. During harvest, berries should be collected thoroughly from coffee bushes and the plantation floor. Fallen berries, overripe berries and leftover fruits can serve as breeding reservoirs for the pest, making thorough harvesting and field sanitation important components of CBB management (Aristizabal *et al.,* 2016; Johnson *et al*., 2020). This practice is particularly important because CBB populations can survive between crop periods inside leftover berries. Gleaning - spreading gunny bags or polythene sheets on the ground after picking the berries.
2. Proper drying and post-harvest management: Coffee should be dried to the prescribed moisture level. Proper drying can help kill insect stages remaining inside harvested berries and reduce the possibility of pest survival during post-harvest handling. The Coffee Board

has indicated approximately 10.5% moisture for parchment and 11% for cherry coffee in its management guidance.

3. Monitoring with Alcohol based (Broca) traps: Broca traps are useful for monitoring adult CBB activity and supporting population surveillance and management decisions (Aristizábal *et al*., 2016; Johnson *et al.,* 2020). Traps can help growers determine pest activity and identify areas requiring special attention. The Coffee Board recommends Broca traps at approximately 25 traps per hectare for field and drying-yard management under its current planter guidance.
4. Biological control using Beauveria bassiana: The entomopathogenic fungus Beauveria bassiana is an important biological control agent against CBB. The fungus infects adult beetles and can contribute to suppression of populations, although efficacy depends on strain, environmental conditions and application efficiency (Aristizabal *et al*., 2016; Wraight *et al*., 2021; Moreno-Ramirez *et al.,* 2024).
    a) Mix 500 ml of groundnut oil with 500 ml of any agricultural wetting agent thoroughly.
    b) Add this suspension to 20L of water and three bags of *Beauveria* culture the above solution mix well and strain through a muslin cloth.
    c) Application of spore suspension on the infested coffee bushes using a sprayer, targeting the berries.
    d) After 5 days application spores germinate and kill the insect.

For practical field management, growers can follow a simple sequence

Maintain plantation sanitation → Pest Monitoring → Install pheromone traps → Apply biological control when appropriate → Harvest completely → Remove leftover berries → Proper drying of harvested coffee

Conclusion

Coffee berry borer, *Hypothenemus hampei* is a minute but highly destructive pest of coffee. Early detection, proper harvesting, removal of leftover berries, Broca trapping and biological control with *Beauveria bassiana* are important components of an integrated pest management practice.

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CORAL REEFS: THE TROPICAL RAINFORESTS OF THE SEA

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Abstract
Coral reefs are among the most diverse, productive and ecologically important marine ecosystems on Earth. Often called the "tropical rainforests of the sea," they support thousands of marine species and provide essential habitats for a wide range of organisms. Corals are animals belonging to the phylum Cnidaria and occur as hard, reef-building corals and soft, non-reef-building corals. Reef ecosystems are distributed mainly in tropical regions, including important reef areas in India. Coral reefs develop as fringing reefs, barrier reefs and atolls. Understanding coral biology, feeding, reproduction and reef formation is essential for appreciating their ecological importance and promoting effective conservation of these valuable marine ecosystems.

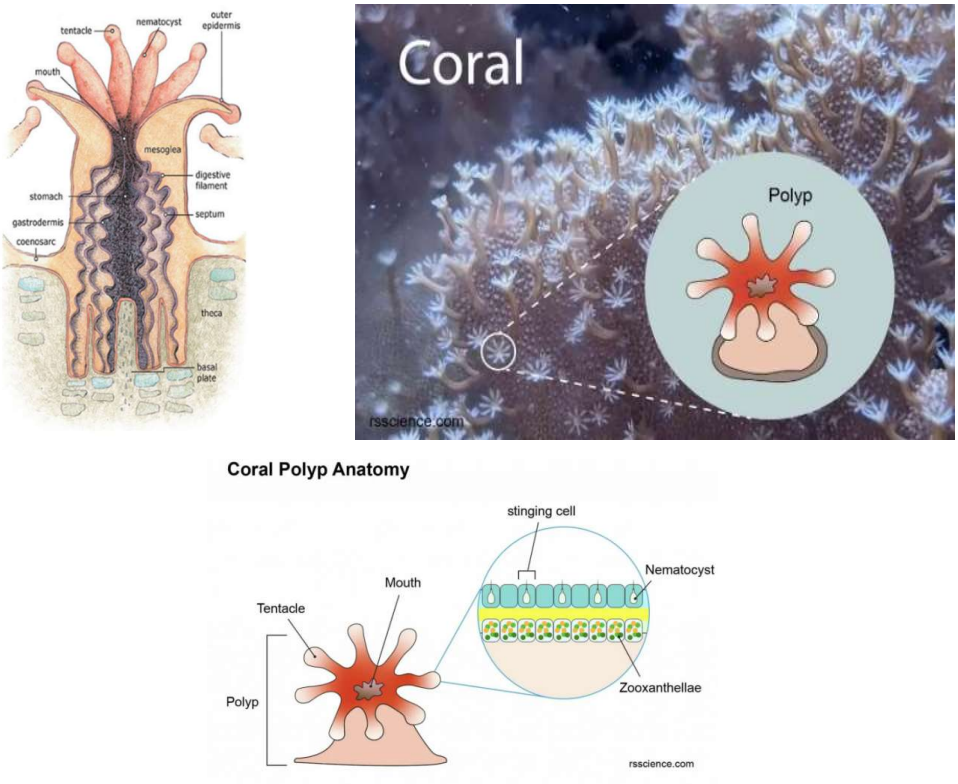
Introduction
Corals are animals, even though they may exhibit some of the characteristics of plants and are often mistaken for rocks and they are relatives of jellyfish and anemones. Coral reefs are the most luxuriant and complex of all benthic communities and they are found all around the world. The term "coral reef" generally refers to a marine ecosystem in which the main organisms are corals that house algal symbionts within their tissues. These form the largest biogenic reefs in the world. These are the largest living structures (biogenic reef) on earth, and there are over 4000 species of reef fish, making coral reefs the home for one fourth of all the fish species found on the earth.

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 resemble tropical rainforests in the following ways:

- Both thrive under nutrient poor conditions yet support rich communities through incredibly efficient recycling processes
- Both exhibits very high levels of species diversity
- Coral reefs are noted for some of the highest levels of total (gross) productivity on earth. The net primary productivity of coral reefs is approximately 2500 grams of carbon per square meter per year, compared to 2200 grams of carbon per square meter per year for tropical forests and only 125 grams of carbon per square meter per year in the open ocean.

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Most of the coral colonies are comprised of many small soft, jelly-like bodies of individual animals, called as polyps and only small species live as solitary individuals. The extraordinary diversity of reefs makes them biologically important and like rainforests they have provided valuable scientific insights into the nature of underwater ecology. It is a diverse collection of species that interact with each other and the physical environment. The sun is the initial source of energy for this ecosystem. They are considered to be one of the most sensitiveto any change. When they are environmentallystressed, they lose much of the algae that gives them the colour along with other pigments. When this happens,the corals appear white in colour and are referred to as bleached.

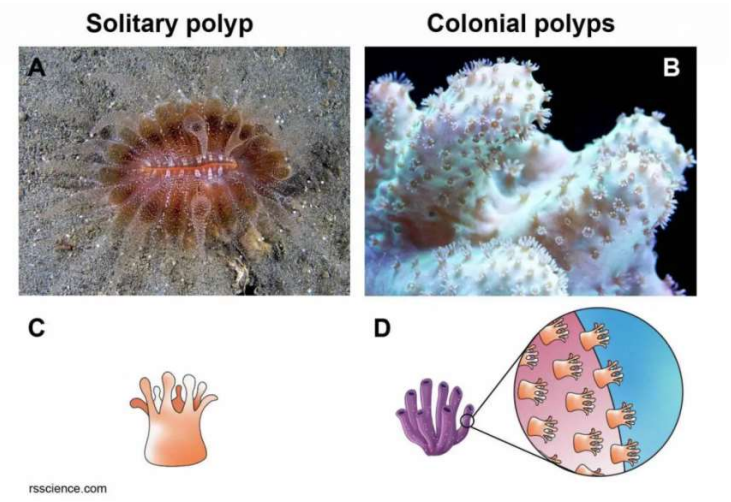


Figure: (A) Polyp of the solitary coral Flabellum sp, (B) A colony comprised of many individual polyps (finger leather coral), (C) Illustration of single solitary polyp, (D) Illustration of polyps forming a colony.

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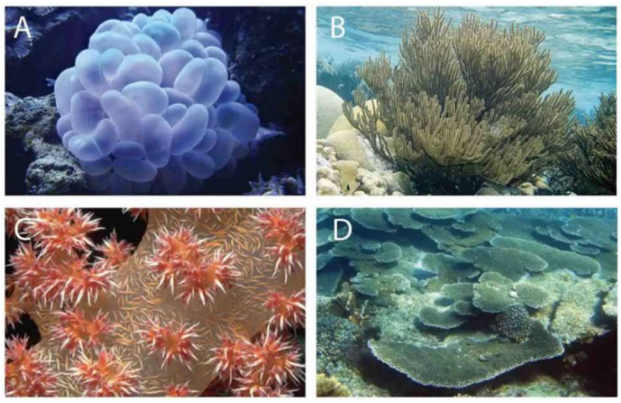


Figure: Examples of coral colonies with different shapes: (A) bubble coral, (B) sea rod coral, (C) orange soft coral, and (D) plate coral.

Scientific classification

Kingdom	Animalia
Phylum	Cnidaria
Class	Anthozoa (corals and anemones)
Subclass	Hexacorallia (hard corals)
Order	Scleractinia (stony corals)
Subclass	Octocorallia (soft corals)
Order	Alcyonacea (soft corals)

Distribution of coral reefs

Coral reefs occur throughout the tropical region on either side of the equator where conditions favour their growth. The coral reefs of the central Indo-pacific and the Caribbean hold the greatest diversity of marine life. The most diverse region of the world for coral reefs is centred on the Australia, Philippines, Indonesia, Malaysia and Papua New Guinea with between 500-600 species of corals. Large portions of world's coral reefs occur within the Indian ocean.

India has four major reef ecosystems having all three reef types, atoll, fringing and barrier. The total area of coral reef in India is estimated to be about 2,375 km2 which is less than 1 % of all the coral reef areas in the world. The mainland coast of India has two widely separated areas containing reefs, the Gulf of Kuchh is located in the northeast (Gujarat state) and the Palk Bay and Gulf of Mannar are located in the southeast (Tamil Nadu state). The Andaman and Nicobar Islands in Bay of Bengal have fringing reefs around many islands and a long barrier reef (329 km) on the west coast. The Lakshadweep in the Arabian Sea also has extensive reefs especially atolls.

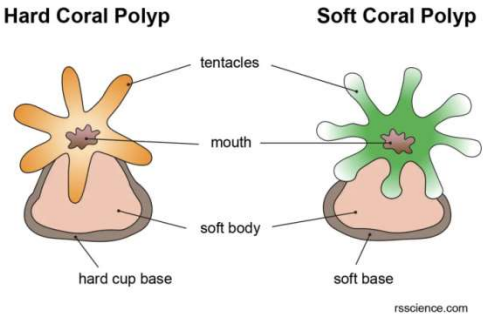
Types of corals

There are two main types of corals: non-reef builders or Alcyonacea (ahermatypic) and reef builders or Scleractinia(hermatypic). Ahermatypic corals and solitary hard corals and they do not form reefs as they do not possess the symbiotic algae, zooxanthellae in its internal body wallwhich are present in aphotic zone. Soft corals are colonial corals that have a flexible skeleton and depend on toxic chemicals in their tissues to protect themselves from predators. Soft coral colonies tend to resemble trees, bushes, fans, whips and grasses.

Hermatypic corals are reef forming corals and this is possible for them because they are known to havezooxanthellae in their body wall. These are hard corals that form large colonies from thousands

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of connected polyps living together, sharing food an energy. Hard corals use zooxanthellae to combine calcium and carbonate from the water and for respiration. The zooxanthellae are coral's solar panels and provide enough energy to build their skeletons rapidly. Generation after generation of polyps add to the skeleton, corals are known to attain variety of shapes and sizes. Coral colonies can grow bigger than a small house and can be several hundred years old. Over thousands of years, the skeleton of many coral colonies living together form reefs.



Both hard coral polyps and soft coral polyps have soft bodies with a month and multiple tentacles. Hard coral polyp holds itself in place by its hard cup base, while soft coral polyp uses its soft base. Hard corals have 6 tentacles while soft corals have 8 tentacles.

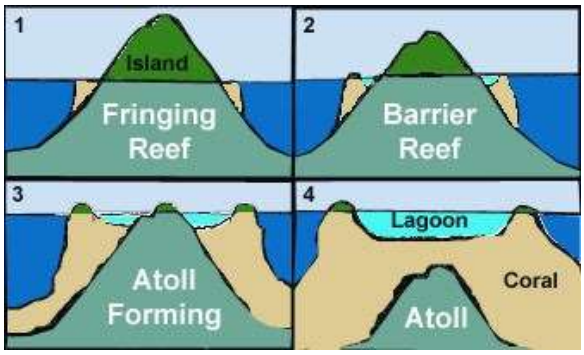
Examples for hard and soft corals	
Hard corals	**Soft corals**
Staghorn coral - *Acropora cervicornis*	Sea fan - *Gorgonia ventalina*
Table coral – *Acropora* sp	Toadstool coral
Brain coral	Tree coral
Elkhorn coral - *Acropora palmata*	Sea pens – *Pennatula phosphorea*

Formation of coral reefs

There are three major types of reefs: fringing reefs, barrier reefs and atolls.

I. Fringing reefs extend along the shoreline, close to land or separated only by a narrow stretch of water, but that can extend out to sea long distances. This reef type exists in shallow waters.

II. Barrier reefs form farther offshore usually 10-100 kilometers from the coast and often form massive walls of coral separated from the coast by alarge channel or lagoon.



Atolls are circular reefs surrounding a lagoon that form when volcanic islands sink into the ocean over millions of years.

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Feeding of corals

During feeding, a coral polyp will extend its tentacles out from its body and wave them in the water current where they encounter zooplankton, bacterioplankton, or other food particles.A coral's prey is typically microscopic zooplankton.

Reproduction in corals

A coral colony may consist of thousands of polyps. Polyps are typically carnivorous, feeding on small particles floating in the water. Corals reproduce both sexually and asexually.

a) Sexually – Broadcast spawning

An entire colony many meters in diameter can start out as a single polyp. On a few nights of each year, many of the corals on the reef reproduce in an event called mass spawning. Ten to hundreds of species of corals release their eggs and sperm into the water on the same night. The eggs float to the ocean's surface where they can be fertilized, forming new coral larvae called planulae.

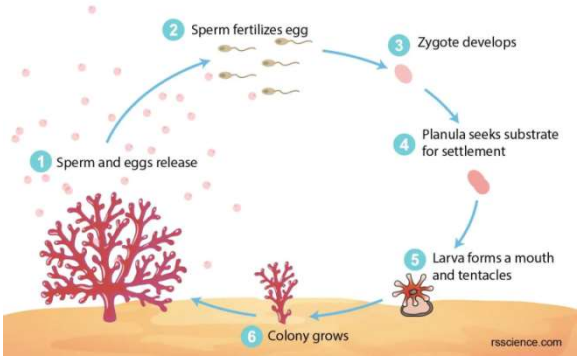


Figure: (1) The mature corals synchronize their spawning to release gametes bundles, which contain sperm and eggs. (2) Sperm fertilize eggs. (3) Fertilized eggs undergo cell divisions. (4) Planulae larvae drift with current for days to weeks and actively seek suitable substrate to settle down. (5) Larvae form mouths and tentacles. (6) Polyps grow their colonies through polyp budding.

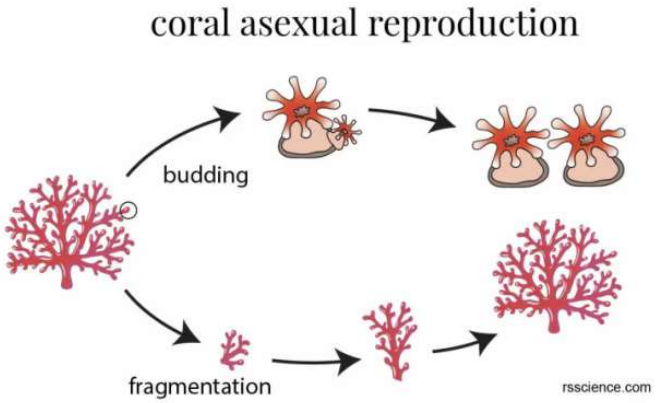
b) Asexually – Budding

The coral planulae swim in the ocean for several days to also reproduce asexually by budding. During budding the coral polyp will divide to make a nearly identical copy of itself that will remain attached to the parent polyp. A coral colony will form after repeated rounds of budding and can grow to contain hundreds and even thousands of polyps. As new polyps form they overgrow older polyps that die and add their calcium carbonate skeleton to foundation of the reef.

c) Asexually – Fragmentation

This method also allows a portion of an entire colony to establish a new colony.If a portion of a larger colony is broken off from the main colony during a storm or boat grounding, the separated individuals can start new coral colonies that are genetically identical to the parent colony. However, the success of the fragments in establishing a new colony is dependent upon whether they are exposed to favourable growth conditions. For instance, fragments exposed to strong wave action will find it difficult to settle on a substrate for continued growth.

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COVER CROPS – LIVE MULCHES OF MULTI-SERVICE PARADIGM IN VEGETABLES

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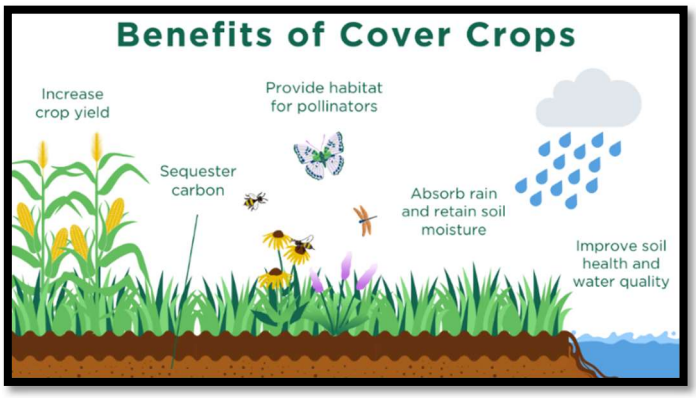
Introduction

The increasing use of pesticides in modern agriculture has given farmers a comprehensive technology package for increased yields. Although intensive agriculture enhanced agricultural output, it also had a large negative impact on environmental problems, such as global warming. Farmers all over the world are becoming more and more entangled in a vicious cycle of sustainability that is brought on by the exploitation and degradation of land and water resources, rising manpower and input costs, and dwindling profit margins. Vegetable quality and yield are both reduced by a number of production issues (Mennan *et al.,* 2020). A few abiotic factors that affect vegetable productivity are salinity, drought stress, and climate variations, while the main biotic contributors are disease pathogens, insect pests, viruses, and weeds. Improved cover cropping system integration with current agricultural practises may serve as the bedrock of sustainable agro-ecosystems in this context.



Cover crops

The usage of cover crops dates back to ancient times. Early Romans were accustomed to cultivating bell beans in the vine yards. Ancient literature from India and China that date back three thousand years well-document the cultivation of cover crops there as well. In his work "A Tomb on All Aspects," written between 70 and 19 BCE, Virgil noted that lucerne, clovers, and lupine can all be employed to boost wheat production. Cover crops are plants grown in fields so that they provide soil cover whether they are actually incorporated in the soil or not. They also help to prevent soil erosion, limit weed growth, increase soil fertility and quality, and manage pests and disease infestations (Singhal *et al.,* 2020).



The idea behind cover crops is to provide soil with a covering that affects the germination of nearby seeds by altering their habitat, such as the amount of light available, the soil's temperature and moisture, and other factors like allelopathy. Various plant growth-promoting properties are brought

about by the functional diversity of bacterial communities found in the rhizosphere of various cover crops, including the activation of nutrients in soils, production of numerous plant growth regulators, defence against phytopathogens, improvement of soil structure, sequestration of toxic heavy metals, and degradation of xenobiotic compounds.

Applications of cover crops in vegetables

Weed suppression

Cover crops play a major role in organic vegetable production systems for weed reduction. They reduce weeds through root exudates and decomposing residues interfering in the growth and development of main crop. Rye grass oat and common vetch has been found to reduce the weed population upto 73 % in organic pepper. In cucumber, cereal rye, sudangrass were used to eradicate weeds. Tomato when grown with cover crops like hairy vetch, oat and subclover had about 79 – 93 % weed control. Pumpkin when integrated as a cover crop in cassava reduced the weed population by 30 – 60%. These cover crops through allelopathic effects suppresses the living ability of weeds. The crops having canopy structure complementary to the main crop will exhibit better cover-crop performance.



Oats cover crop in radish



Cereal rye in Soyabean

Disease reduction

By obstructing several stages of the disease cycle, including dispersal, host infection, disease development, propagation, population accumulation, and pathogen survival, cover crops prevent the spread of illness. The ability of these crops to host or inhibit pathogens is a requirement for building cover-crop systems explicitly for disease management. In alternate situations, the cover crops may act as a host for the pathogen but not as an actual disease carrier. In the event that they are improperly degraded, the population of pathogens like *Pythium spp*. grows, leading to serious epidemics. Marigold (*Tagestes patula*) reduces early blight disease in potato. Rapeseed and canola (*Brassica napus*) are used to reduce rhizoctonia canker, black scruf and common scab in potato. Hairy vetch (*Vicia villosa*) controls fusarium wilt in watermelon. Rye (*Secale cereale*) reduces the effect of powdery mildew, plectosporium blight and black rot in conventionally tilled pumpkin. Broccoli as a cover crop reduces viable sclerotium density causing white rot disease in garlic.

Pest and Insect control

Changes in the biophysical quality of the soil, the creation of favourable niches for beneficial species, the production of toxic exudates, and changes in soil ecology all play a role in how cover crops function as biological control agents. By creating more hospitable conditions for free-living fungivores, bactivores, and other predators, cover crops help improve biodiversity. Mulch crops

prevent the spread of olfactory and visual cues released by host plants, which reduces pest proliferation and improves insect pest suppression. *Medicago sativa* (Alfalfa) has been known to eradicate corn borer and acts as a natural enemy for the egg and larval stages of caterpillars in broccoli. White clover acts against aphid infestation in leek, flea beetle in broccoli and lepidopteran pests of crucifers. Basil reduces the pest population of aphids in broad beans. Sunn hemp (*Crotolaria juncae*) acts against watermelon mosaic virus in pumpkin, lesser corn stalk borer and nematodes in cucumber. Cowpea suppresses the pest population of pepper.

Constrains in cover crop technology

Although such systems have many advantages, there are a number associated difficulties as well. Reduced production may be the result of competition between living mulches and the main crop. Such systems may negatively affect returns, particularly for commodities with a short shelf life and high value like vegetables where yield reduction owing to competition may dramatically affect premiums in prices (Haider *et al.,* 2019). Employing cover crops will reduce the amount of remaining soil moisture in water-stressed areas, which may lower the yields of commercial crops. Winter crops used as live mulch in semi-arid circumstances decreased soil water storage by 65–74 mm, affecting the demand for pre-irrigation of succeeding crops and/or the productivity of succeeding annual crops. The residues of cover crop may hamper the germination of vegetables seeds during the next season. High biomass production affects the intercultural operations of the main crop. Understanding the practical barriers that prevent producers from implementing live mulch technology and disseminating information on and management abilities for employing this technology will aid in its wider adoption.

Conclusion

The adoption of conservation agriculture is urgently required to address the issues brought on by inorganic farming. Given the importance of integrated soil management as an integral component of sustainable agriculture, cover crops are being accepted as a crucial part of conservation farming. However, the knowledge and expertise required to use cover crop technology are still in their infancy. Farmers need to receive training in order to raise awareness and strengthen their skills. For broad use of cover crops in cropping systems, a set of best practises for their use in general or for addressing specific types of problems at the regional and global levels is required.

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SPECTACULAR CRAB SPIDER PREDATION ON HONEY BEE (*Apis cerana indica*) ON SWEET BASIL

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Abstract

Spectacular Crab spiders (Family: Thomisidae) are important ambush predators in terrestrial ecosystems and are commonly associated with flowers and foliage where they prey on visiting insects. The present article documents the predation of the spectacular crab spider (*Thomisus spectabilis*) on the Asian honey bee (*Apis cerana indica*) observed on sweet basil (*Ocimum basilicum*). Crab spiders possess laterigrade legs, strong anterior limbs and venomous chelicerae, which enable them to rapidly capture and immobilize suitable prey. Their cryptic body colouration and sit-and-wait hunting strategy facilitate successful encounters with flower-visiting insects. Honey bees, while foraging for nectar and pollen, may become vulnerable when they approach flowers occupied by crab spiders. The floral environment of sweet basil can therefore function simultaneously as a foraging site for pollinators and a hunting site for predators. This observation highlights the ecological interaction between a flower-associated predator and an important pollinator. Although individual predation events may occur, they do not necessarily indicate a significant threat to honey bee colonies. Management around apiaries should emphasize ecological balance, monitoring of crab-spider abundance and avoidance of unnecessary broad-spectrum pesticide applications. Maintaining floral diversity and conserving beneficial arthropods may support a balanced arthropod community. Proper identification of crab spiders is essential before implementing specific management measures.

Keywords: Crab spider; Sweet basil, Honey bee

Introduction

Spiders are important predators in terrestrial ecosystems and contribute significantly to the natural regulation of arthropod populations. Unlike many insect predators, spiders generally do not require specialized prey and can consume a wide range of insects. Their ecological importance is therefore particularly relevant in agricultural ecosystems where numerous insect species occur simultaneously. Among the diverse spider families, Thomisidae**,** commonly known as crab spiders, are especially interesting because many species use an ambush-predation strategy. They commonly occupy flowers, leaves, bark and other plant surfaces and wait for suitable prey to approach. Their enlarged front legs and laterally directed legs give them a crab-like appearance, which is responsible for their



Spectacular Crab spider predating on *A. cerana indica*

common name. Crab spiders are well known for preying on flower-visiting insects, including bees. For example, *Thomisus spectabilis* has been experimentally studied as a predator of honey bees, and its position and colouration on flowers can influence encounters with pollinating insects (Heiling *et al*., 2005). The present observation is particularly interesting because the predator was photographed on sweet basil **(***Ocimum basilicum***)** while feeding on *Apis cerana indica***.** Basil is a flowering plant visited by bees and other insects.

General Morphology of *Thomisus spectabilis* (Spectacular Crab Spiders)

Crab spiders are generally small to medium-sized spiders with a compact, somewhat flattened body. They are named "crab spiders" because their first two pairs of legs are usually longer and stronger and are often held laterally, giving them a crab-like appearance. Their body consists of two main regions: the cephalothorax (prosoma**)** and abdomen (opisthosoma)**.**

Eyes

Thomisids possess four pairs of eyes (eight eyes) arranged on the cephalothorax. The eyes are relatively small compared with those of jumping spiders. Vision is important for detecting approaching prey and predators, although crab spiders primarily depend on ambush predation and camouflage rather than active visual pursuit.

Body and Colouration

The body is generally compact, flattened and often cryptically coloured. Many species show white, yellow, brown, greenish or mottled colouration that blends with flowers, leaves or bark. Some crab spiders can change their body colour according to the background, improving camouflage (crypsis) and reducing detection by both prey and predators.

Legs

The most characteristic feature is the laterigrade arrangement of the legs. The first and second pairs are usually longer and more robust than the posterior legs and are held sideways. These strong forelegs are adapted for grasping and holding prey. Crab spiders generally do not build webs for capturing prey and instead wait for suitable insects to approach.

Chelicerae

The chelicerae bear sharp fangs used to seize and penetrate prey. During predation, the crab spider grasps the insect with its strong anterior legs and delivers a bite through the chelicerae. Venom is injected into the prey and helps in immobilization and digestion.

Silk

Crab spiders generally do not construct prey-catching webs. However, like other spiders, they produce silk for various purposes, including attachment to the substrate, movement and construction of protective structures or retreats. Silk may also provide an attachment point while the spider occupies a hunting position.

Abdomen

The abdomen is usually soft and relatively broad, and its shape and colour vary among species. In flower-dwelling species, the abdomen may be white, yellow or patterned, helping the spider blend with the floral background.

Hunting Adaptation

Crab spiders are primarily sit-and-wait (ambush) predators. They often position themselves on flowers or foliage where pollinating insects such as bees, flies and butterfly's visit. When an insect comes within striking distance, the spider rapidly extends its forelegs, grasps the prey and bites it.

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***Thomisus spectabilis* as a Predator**

Spectacular Crab spiders (Family: Thomisidae) are primarily sit-and-wait or ambush predators. Unlike spiders that construct prey-catching webs, they usually position themselves on flowers, leaves or other plant surfaces and wait for suitable prey to approach. Their laterigrade legs, particularly the strong first two pairs, are well adapted for rapidly grasping and holding insects. Crab spiders are known to prey on pollinating insects, including honey bees. Heiling *et al*. (2005) reported that *T. spectabilis* ambushes pollinating insects such as honey bees on flowers. Their cryptic body colouration can help them remain inconspicuous while waiting for prey. Spectacular crab spiders do not attack every insect that approaches them. Successful predation depends on factors such as prey size, distance, movement, position of the spider, camouflage and timing of the attack**.** When a suitable insect approaches within striking distance, the spider rapidly extends its strong anterior legs, grasps the prey and delivers a bite.

Honey Bee: *Apis cerana indica*

Apis cerana indica is an important Asian honey bee that forages actively on flowering plants for nectar and pollen. During foraging, worker bees frequently visit flowers and inflorescences, making them potential targets for flower-associated predators such as spectacular crab spiders**.**

Crab spiders commonly occupy flowers, leaves and other parts of vegetation and adopt a sit-and-wait strategy. When a honey bee approaches a flower to collect nectar or pollen, it may come within the striking range of a concealed crab spider. The spider can then rapidly extend its strong anterior legs, grasp the bee and deliver a venomous bite, eventually immobilizing and consuming the prey.

The interaction between *A. cerana indica* and crab spiders is particularly relevant in flowering plants such as sweet basil (*Ocimum basilicum***)**, where both pollinators and flower-associated predators may occur. The floral environment therefore functions simultaneously as a foraging site for the bee and a hunting site for the spider**.**

Management Considerations in Apiaries

If a spectacular crab spider is occasionally observed preying on *Apis cerana indica* around an apiary or on flowering plants such as *Ocimum basilicum*, immediate removal of all crab spiders is generally unnecessary. Spectacular crab spiders are natural predators of flower-visiting insects, and individual predation events do not by themselves demonstrate a significant threat to honey-bee colonies (Heiling *et al*., 2004; Heiling *et al*., 2005).

The following management principles may be considered:

- **Avoid unnecessary broad-spectrum pesticide application** around apiaries, as pesticides can affect honey bees and other beneficial arthropods.
- **Maintain diverse vegetation** around the apiary to provide floral resources and support a balanced arthropod community.
- **Monitor crab-spider abundance** rather than reacting to individual predation events.
- **Record repeated predation** near flowering plants or hive entrances if crab spiders appear unusually abundant.
- **Avoid indiscriminate destruction of crab spiders** in surrounding vegetation, because they are natural predators and form part of the local arthropod food web.
- **Maintain biodiversity** around the apiary to support ecological balance.
- **Confirm spider identification** before implementing any specific management measure, because different spider families have different behaviours and ecological roles.

Conclusion

The present observation of *Thomisus spectabilis* preying on *Apis cerana indica* on sweet basil (*Ocimum basilicum*) highlights the ecological relationship between flower-associated predators and pollinating insects. Crab spiders are well adapted to ambush predation through their strong anterior legs, laterigrade leg arrangement, cryptic colouration and venomous chelicerae. Sweet basil flowers provide foraging resources for honey bees while simultaneously serving as hunting sites for crab spiders. Although such predation may affect individual foraging bees, a single observation does not establish a significant threat to honey bee colonies. Therefore, indiscriminate removal of crab spiders or unnecessary pesticide application around apiaries should be avoided. Monitoring spider abundance, confirming species identification and maintaining floral diversity are important components of ecologically balanced apiary management. Further observations and systematic studies are needed to understand the frequency, extent and ecological significance of crab spider predation on *A. cerana indica* under field conditions.

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PRACTICAL GUIDANCE ON VERMICOMPOSTING

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What is vermicomposting?

Vermicomposting is the process of using certain types of earthworms to break down organic waste (such as crop residues and vegetable wastes) into a nutrient-rich material called vermicompost, which improves soil fertility and plant growth. Vermicomposting turns farm and kitchen waste into rich compost using earthworms. It happens in four stages.

- First, farm organic wastes are collected. This includes farmyard manure, crop residues, and agro-wastes. These materials are pre-decomposed before use. Pre-decomposition means the waste is left to partially break down first since fresh waste is too hot and acidic for earthworms. Partial breakdown makes it safe for them.
- Next, composting earthworms are introduced into prepared vermicomposting beds. These beds are set up with proper bedding and moisture. Common earthworm species include *Eisenia fetida, Eudrilus eugeniae,* and *Perionyx excavatus.*
- Once earthworms are in the bed, they feed on the organic waste. As they eat and digest it, they convert it into nutrient-rich vermicompost. Their gut adds beneficial microbes and enzymes to the material. This is what makes vermicompost more nutrient-dense than regular compost.
- Finally, the mature vermicompost is harvested. It is sieved to remove any leftover earthworms or large particles. The finished product is then applied to fields. It improves soil fertility and boosts crop productivity over time.

Five basic requirements for earthworms

- Food source
- Adequate moisture
- Adequate aeration
- Protection from heat
- A hospitable environment (bedding)

Inputs for vermicomposting

- Biodegradable waste:
    - Leaf litter
    - Crop residues
    - Weed biomass
    - Vegetable waste
    - Kitchen waste
    - Waste from agro-industries
    - Biodegradable urban and rural wastes

- Cow dung
- Suitable earthworm
    - *Eisenia foetida* (red worms)
    - *Eudrilus eugeniae* (African earthworms)
    - *Perionyx excavatus* (Asian worms)
- Suitable site (cool, shady place; thatched roof to protect from sunlight and rain)
- Bedding materials

Characteristics of good bedding materials

Good bedding material should have high absorbance. It should hold enough moisture for the earthworms to stay active. It also needs good aeration, so that air can move through the bed and reach the worms. The material should have a high C:N ratio. That means it should be low in nitrogen and protein. If nitrogen and protein content is high, the waste degrades too fast. This raises the heat in the bed, and the worms end up dying from that heat. Common bedding materials include *sawdust, coir waste, sugarcane trash, waste newspaper, paper mill sludge, dry leaves, and straw.*

Methods of vermicomposting

There are several ways to set up a vermicomposting unit. The choice depends on space, cost, and scale.

- **The pit method** uses a pit dug below ground level. It is simple and low-cost, but drainage and aeration need care since it sits below ground.
- **The trench method** is similar. A trench is dug below ground and filled with bedding and waste. It works well for larger volumes of waste.
- **The indoor heap method** builds the compost as a heap above ground, inside a covered structure. This protects the bed from rain and direct sun.
- **The outdoor heap method** also piles the material above ground, but in the open. It needs some form of shade or cover to protect it from heavy rain and sun.
- **The tank method** uses a built tank, often made of brick or concrete, to hold the bed. Tanks are durable and easy to manage, and are commonly used at demonstration units and larger farms.
- **The ring method** uses cement or plastic rings stacked to form a round enclosure for the bed. It is compact and works well for small-scale production where space is limited.
- **The bin, basket, or pot method** uses containers like drums, baskets, or pots. This suits small households or kitchen-scale composting, since it needs very little space.
- **The HDPE rectangular method** uses long, flexible HDPE vermicomposting bags as the composting units, with pre-decomposed organic feedstock placed directly inside. Earthworms are introduced into the material, and the bags help retain moisture, minimise seepage, and provide a simple, space-efficient system that can be installed in rows for larger-scale production.
- **The HDPE ring method** is similar, but the HDPE sheet is arranged to form a circular vermicomposting bed or ring, with the pre-decomposed feedstock placed directly inside. Like the HDPE bag/bed system, it is simple to install, relatively low-cost, lightweight, and easy to relocate, making it suitable for small- to medium-scale vermicomposting.

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Fig. 1 Pit, trench, and heap methods of vermicomposting

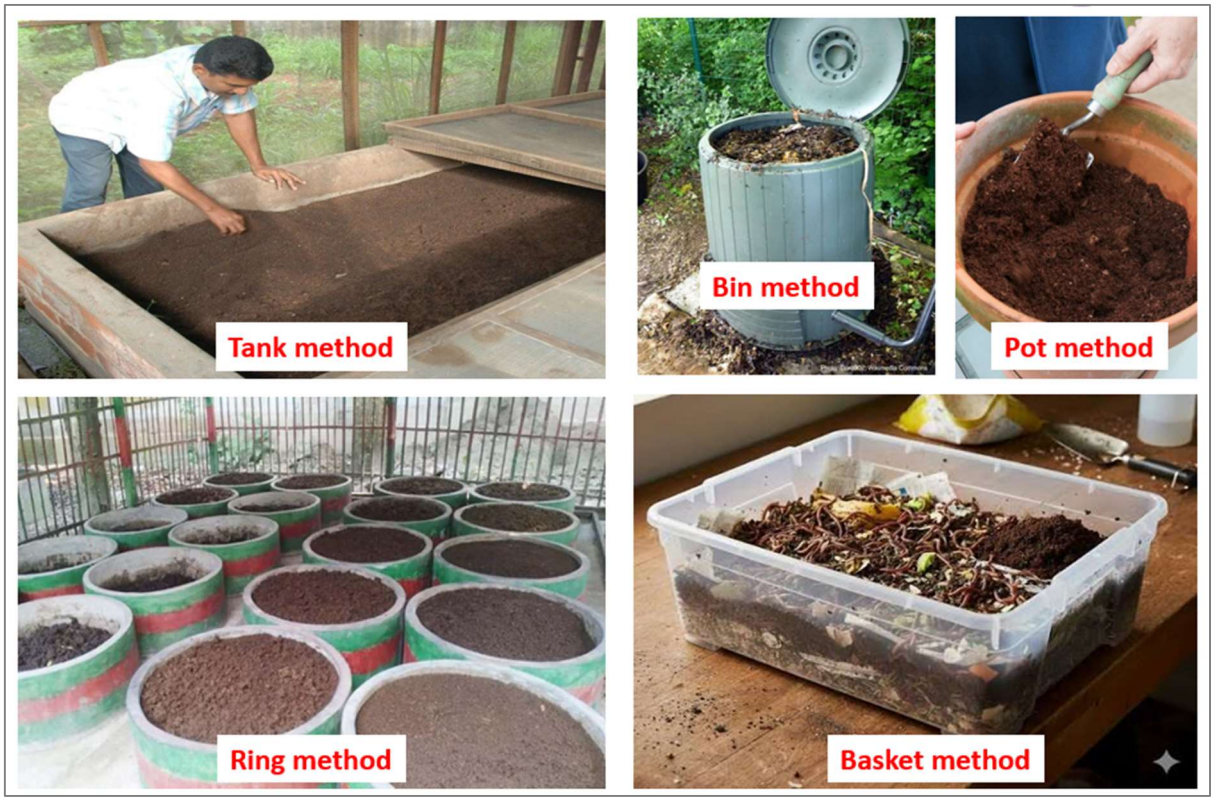


Fig. 2 Tank, ring, bin, basket, and pot methods of vermicomposting

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Fig. 3 HDPE method of vermicomposting

Steps in vermicomposting

Vermicomposting runs in four phases, from feedstock preparation to final harvest.

Phase I (Pre-decomposition and layering): This step involves feedstock preparation and takes about 15 to 30 days. It starts with collecting the waste. The waste is then segregated to remove metal, glass, polythene, and other non-biodegradable materials. Fresh vegetable waste with high moisture is dried before use. The waste is shredded or chopped into small sizes, since smaller pieces break down faster and are easier for earthworms to feed on.

Pre-decomposition: Pre-decomposition is the initial microbial breakdown of organic feedstock carried out before introducing it into the vermi-bed. In this step, the dried and shredded crop residues are mixed with cow dung. Soft wastes are mixed at a 3:1 ratio, while more resistant wastes are mixed at a 5:1 ratio. This waste-and-cow-dung mixture is left to pre-decompose for about 15 to 30 days. During pre-decomposition, the feedstock is partially digested, making it ready for earthworms to consume. This process of pre-decomposition generally passes through four temperature phases:

1. Initial mesophilic phase (20–40°C): Pre-decomposition begins with the rapid multiplication and activity of mesophilic microorganisms. They break down readily degradable organic matter, and their metabolic activity generates heat, causing the temperature of the feedstock to rise.

2. Thermophilic phase (45–70°C): As the temperature increases, thermophilic microorganisms become dominant, and decomposition becomes highly active. The elevated temperature helps reduce many pathogens and weed seeds present in the feedstock. This phase also accelerates the breakdown of easily decomposable organic matter such as sugars, starches, proteins, and some fats.

3. Cooling and second mesophilic phase: After the thermophilic phase, microbial activity and heat generation gradually decline, causing the temperature to fall. As the material cools, mesophilic microorganisms become active again and continue the decomposition process. More resistant materials (e.g., cellulose and some lignocellulosic compounds) are progressively decomposed as temperature falls. The feedstock should be allowed to cool sufficiently before introducing it into the vermi-bed.

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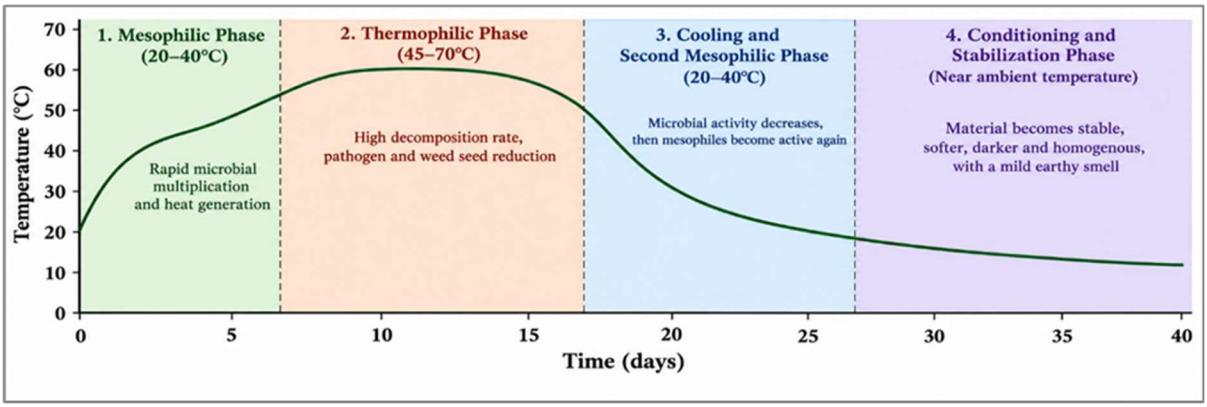


Fig. 4. Phases of thermophilic pre-decomposition in vermicomposting

4. Conditioning and stabilization phase: During this stage, the partially decomposed feedstock becomes more stable and suitable for earthworms. It becomes softer, darker and more homogeneous, and develops a mild earthy smell. When the material has cooled to near ambient temperature and is no longer heating up, it is ready to be transferred to the vermi-bed and inoculated with earthworms.

Note: The material going into the vermi-bed should be pre-decomposed, not fully composted. Earthworms and associated microorganisms will continue the decomposition and stabilization process inside the vermi-bed.

Layering: While the feedstock is pre-decomposed, the vermi-bed is prepared side by side. This bed sits on a concrete base and is built in layers. First comes a drainage layer, made of broken bricks, stones, or chips. Above that goes a bedding layer, made from straw, sawdust, coir pith, sand, sugarcane trash, garden soil, or dry leaves. On top of that goes a layer of pre-decomposed cow dung slurry. Once pre-decomposition is complete, the feedstock is transferred into the vermi-bed. It goes in as layers of 15 to 20 cm of feedstock, each followed by a layer of garden soil and pre-digested cow dung slurry. This layering is repeated until there are three to four layers in total (until the maximum height of the tank).

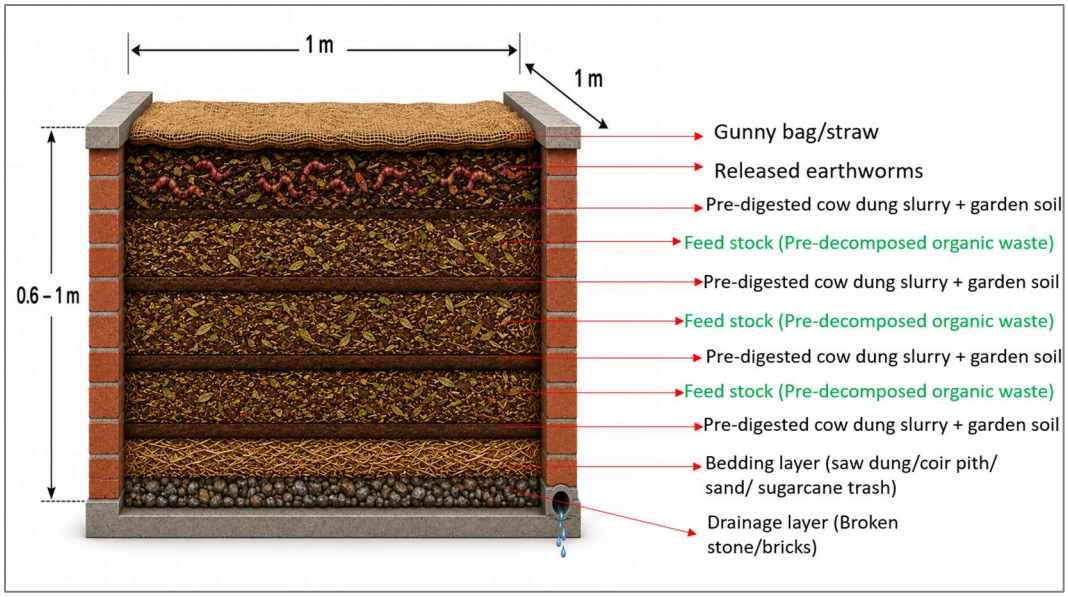


Fig. 5 Layering in vermicomposting

Phase II is earthworm inoculation, and it takes 2 to 5 days. Earthworms are released into the uppermost feedstock layer, at a rate of 1 to 1.5 kg per square meter. Water is sprinkled right after release. The bed is then covered with a gunny bag and watered daily to keep it moist.

Phase III is active vermicomposting, and it runs for 30 to 45 days. Around 20 to 25 days after the earthworms are released, the bed is turned once. This lets air back into the bed.

Phase IV is maturation and harvesting, and it takes about 5 to 10 days. Somewhere between 45 and 60 days after worm release, the compost turns black and granular, with a neutral, earthy smell. This is the sign that it is nearly ready. About 5 to 7 days before the final harvest, watering is stopped. The earthworms then move down to the bottom of the bed on their own. The mature vermicompost is collected from the upper layer and sieved. It can then be mixed with other microbial formulations, such as biofertilizers, before it is packed and marketed. The earthworms are collected using cow dung bulbs and kept aside either to start the next batch or for sale.



Fig. 6 Steps in vermicomposting

Timeline:

The complete process takes approximately 3–3.5 months, allowing around 4 production cycles per year under suitable conditions.

1. Waste Collection & Preparation (Day 0): Biodegradable organic materials such as vegetable and fruit residues, farm wastes, leaves, and other suitable organic matter are collected. Plastics, glass, metals, and other non-biodegradable materials are removed. Bulky materials are chopped into smaller pieces wherever possible.

2. Pre-decomposition & Vermi-bed Preparation (15–30 days): The prepared organic waste is placed in a suitable pile or pre-decomposition bed and is allowed to undergo partial decomposition.

Adequate moisture is maintained, and sufficient aeration is ensured. The vermi-bed is prepared using suitable bedding material before the earthworms are introduced. Fresh, actively heating organic waste is not given directly to the earthworms.

3. Earthworm Release (After 15–30 days of Pre-decomposition): Once the material has cooled and undergone partial decomposition, healthy earthworms are introduced into the prepared vermi-bed. Appropriate moisture and shade are maintained, and the bed is protected from excessive heat, flooding, and predators.

4. First Turning / Aeration (20–25 days after Earthworm Release): The material is gently turned or loosened where necessary to improve aeration and facilitate uniform decomposition. Excessive disturbance of the earthworms and vermi-bed is avoided.

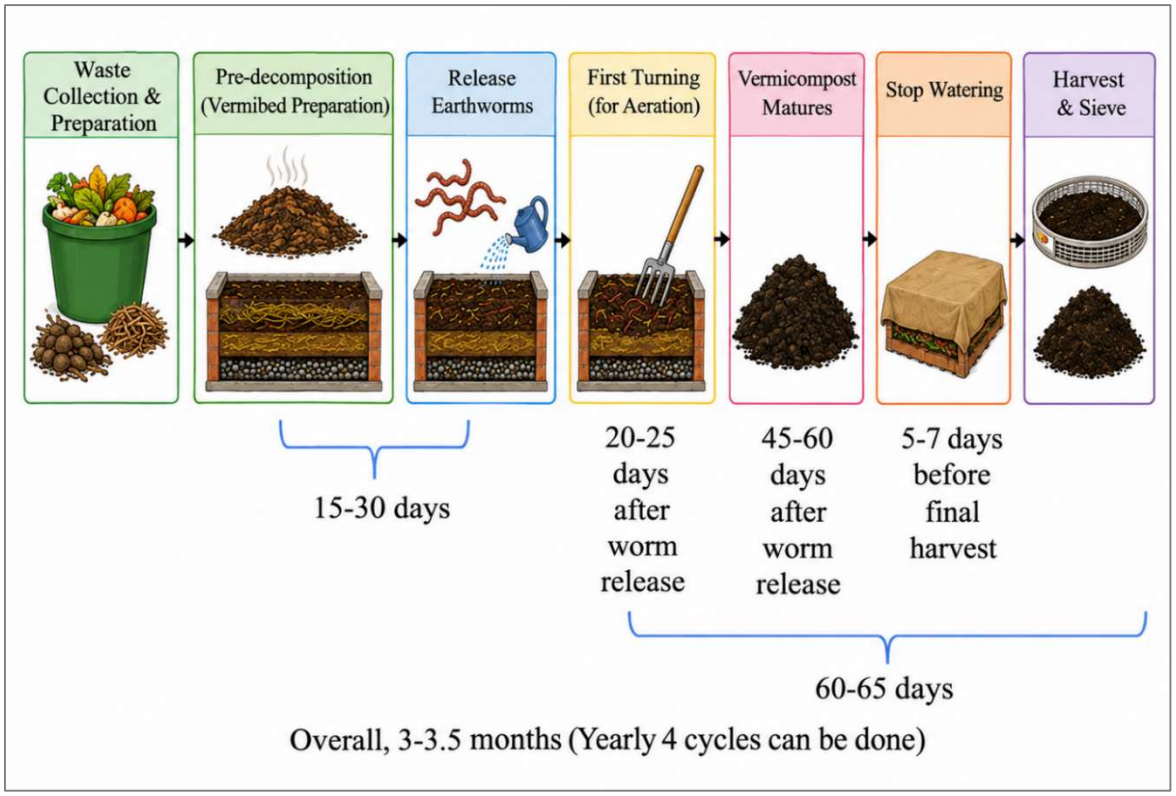


Fig. 7 Timeline of vermicomposting

5. Vermicompost Maturation (45–60 days after Earthworm Release): The organic material is allowed to undergo further decomposition by earthworms and microorganisms. Gradually, the material is transformed into dark, crumbly, earthy-smelling vermicompost. Adequate moisture is maintained throughout this period, and overwatering is avoided.

6. Stop Watering (5–7 days before Harvest): Watering is stopped approximately 5–7 days before the planned harvest. Moisture is thereby reduced, making separation and harvesting easier.

7. Harvest & Sieving (At the End of the Cycle): The mature vermicompost is collected and sieved to obtain a fine, uniform product. Larger undecomposed materials are returned to the next cycle. Earthworms separated during harvesting are also returned to a fresh vermi-bed. The final product is obtained as dark, granular, friable vermicompost with an earthy smell, suitable for use as an organic soil amendment.

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FCO specifications for vermicompost:

Parameters	Values
Moisture, per cent by weight	15.0-25.0
Color	Dark brown to black
Odor	Absence of foul odor
Particle size	Min. 90% material should pass through 4.0 mm IS sieve
Bulk density (Mg m^{-3})	0.7 -0.9
Total OC, % by wt. min.	18.0
Total N, % by wt. min.	1.0
Total P (as P_2O_5), % by wt. min.	0.8
Total K (as K_2O), % by wt. min.	0.8
Heavy metal, (as mg Kg^{-1}), Max.	
Cadmium (as Cd)	5.0
Chromium (as Cr)	50.0
Nickel (as Ni)	50.0
Lead (as Pb)	100.0
C:N	10-15:1

Inputs per tank:

- Crop residue: 240 kg
- Cow dung: 60 kg @ Rs 3/kg
- Earthworm: 1kg @Rs 300/kg
- Soil: 3 kg
- Water: 5-10 lit

Yield:
From a 2×1×0.5 m tank: 200-300 kg vermicompost per cycle

Nutrient value:

- pH: 6.5-7.5
- 1-2: 0.4-0.6:0.5-0.7 N:P:K/ha
- OC: 15-20%
- C: N ratio: 10-15:1

Application dose in the crop field: 2.5 t/ha in field
Precautions:

- Don’t compost meat/fish/other fishy/oily foods (foul odour, heat)

- Use only pre-decomposed feedstock.
- Maintain 60–70% moisture and good drainage.
- Keep the bed under shade.
- Avoid direct sunlight, heavy rain, and waterlogging.
- Avoid plastics, chemicals, pesticides, and non-biodegradable waste.
- Protect from ants, rats, birds, and other predators.
- Turn the bed only when necessary.
- Stop watering 5–7 days before harvest.

Vermi-wash:

Vermi-wash is a liquid organic biostimulant obtained by passing water through a column or bed containing active earthworms and vermicompost.

The collected liquid contains earthworm excretory products, soluble nutrients, beneficial microorganisms, enzymes, plant growth regulators, amino acids, vitamins, and organic acids that promote plant growth.

Composition of vermi-wash:

- Soluble nutrients (N, P, K, Ca, Mg and micronutrients)
- Beneficial microorganisms
- Enzymes
- Amino acids and vitamins
- Plant growth regulators (auxins, cytokinins and gibberellins)
- Humic and fulvic substances

Method of application:

- *Foliar spray:* Dilute 1:10 (1 L vermi-wash + 10 L water) and spray at 10–15 day intervals.
- *Soil drench:* Dilute 1:5 to 1:10 and apply near the root zone.
- *Seed treatment:* Soak seeds in diluted vermi-wash for a few hours before sowing (crop-specific recommendations may vary).

Benefits of vermi-wash application:

- Promotes seed germination and seedling vigour.
- Enhances plant growth and root development.
- Improves flowering, fruiting and crop yield.
- Increases nutrient uptake and photosynthetic activity.
- Enhances resistance to pests, diseases and environmental stress.
- Improves soil microbial activity when applied to the soil.

Precautions for vermi-wash preparation:

- Use only clean, chlorine-free water.
- Do not allow the vermi-bed to become waterlogged.
- Filter the vermi-wash before spraying to avoid nozzle clogging.
- Do not spray during the hottest part of the day.
- Store in airtight containers in a cool, shaded place and use as fresh as possible.

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PRODUCTION TECHNOLOGY OF DAVANA (*Artemisia pallens* Wall.)

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Abstract
Davana (*Artemisia pallens* Wall.), belonging to the family Asteraceae, is an important annual aromatic herb valued for its characteristic delicate fragrance and high-quality essential oil. The crop is predominantly cultivated in southern India, particularly Karnataka, Tamil Nadu and Andhra Pradesh, and its sprigs are widely used in garlands, bouquets and religious offerings. The leaves and flowering tops contain valuable essential oil, with davanone, fenchyl alcohol and davanofuran as important constituents. Davana is mainly propagated through seed, and the use of fresh seed, proper nursery management and transplanting of healthy seedlings are essential for uniform crop establishment. The crop performs well under moderate winter conditions and can be cultivated on soils ranging from sandy loam to medium black soils. Application of 6 t FYM ha^{-1}, 40 kg P ha^{-1}, 40 kg K ha^{-1} and 120 kg N ha^{-1}, along with appropriate irrigation and weed management, supports satisfactory crop growth and productivity. Closer spacing such as 15 × 7.5 cm is suitable for achieving higher herbage and essential oil yield per unit area. Harvesting at about 50 per cent flowering is recommended for maximum oil production. Fresh herbage yield of about 12–13 t ha^{-1} and essential oil recovery of approximately 0.2 per cent under large-scale distillation can be obtained under suitable management conditions. The crop has considerable potential for value addition through essential oil extraction and applications in perfumery, cosmetics, flavouring and religious uses.

Keywords: *Artemisia pallens*, Davana, Essential oil, Aromatic herb, Nursery management

Introduction

Scientific Name : *Artemisia pallens Wall.*
Chromosome Number :2n=16
Family : Asteraceae
Common Name : Davanam (Sanskrit), Marikolundu (Tamil), Davana (Hindi, Kannada)



Davana is an important annual aromatic herb. In India much prized for its delicate fragrance. It is native of South India. Though, it is not systematically cultivated in its home country, it holds key position in production of Davana oil. It grows common in Kashmir valley, Simla, Nainital hills, Karnataka, Tamil Nadu, Uttar Pradesh and Andhra Pradesh. Essential oil of davana acquired considerable reputation in international trade. From Karnataka, Tamil Nadu and Andhra Pradesh oil is exported to USA and Japan. Davana

sprigs are commonly used in garlands, bouquets and religious offering in most part of the year. The leaves and Flowering tops contain the essential oil valued for its exquisite and delicate aroma and is used in high grade perfumes and cosmetics.

The oil content varies among different parts of the davana plant. Flower heads contain the highest oil content at 0.53%, followed by the whole plant, which contains 0.29% oil. The herbage, consisting of leaves and stems, contains about 0.14% oil, based on a two-day air-dried sample. The oil of davana contains hydrocarbons (20%), ester (65%) and oxygenated compounds (15%). The esters are the major constituent responsible for the characteristic smell of davana. Major constituents are like Davanone, fenchyl alcohol, davanofuran. The essential oil of davana which is a brown viscous liquid with rich fruity odour has acquired considerable reputation in the International trade particularly in USA and Japan where it is being used for flavouring cakes, pastries, tobacco and beverages.

Species and varieties: Artemisia is a large, diverse genus of plants, consisting of between 200 and 400 species comprises of mostly herbaceous plants and shrubs, which are known for the powerful chemical constituents in their essential oils.

Artemisia genus includes notable species like *A. vulgaris* (Common mugwort), *A. tridentata* (Big sagebrush), *A. annua* (Sagewort), *A. absinthum* (Wormwood), *A. dracunculus* (Tarragon) and *A. abrotanum* (Southernwood). Most species have strong aromas and bitter tastes from terpenoids and sesquiterpene lactones, which exist as an adaptation to discourage herbivores.

In Tamil Nadu elite local types are popular among the farmers like Nilokottai local, Thevaram local, Thovalai local.

A.annua is a highly cross pollinated crop. Hence, the crop exhibits large variation in maturity, leaf biomass yield and 'artemisinin' content. Many recently released varieties like Asha, Jeevanraksha, Suraksha and Cim-Arogya are recommended for commercial cultivation.

Botany: Davana is an aromatic, erect herb, about 60 cm tall, with much divided leaves and small yellow flowers. The stem and leaves are covered with grayish-white tomentum. The leaves are alternate, petiolate and lobed. The inflorescence is capitulate with flowers which are peduncle to sessile, axillary or forming lax racemes, simple, heterogamous having bisexual disc florets in the centre and a few pistillate ray florets on the periphery.

Climate and Soil: The crop is found growing on various types of soils from sandy loam to medium black. The oil content in the plant was maximum when the crop was grown during the winter season compared to the other seasons. Thus, when the crop is grown for the production of oil it should be planted during the first week of November. A few light showers with moderate winter conditions and no frost is conducive to the good growth of the plant. High temperature and heavy rains at the time of flowering have not only been found to affect the plant growth adversely, but also reduces the oil content and ultimately the oil yield.

Propagation and Nursery Management of Davana: Davana is generally propagated through seeds. Since davana seeds lose their viability quickly, it is best to use seeds from the immediately preceding season for sowing. Approximately 1.5 kg of seed is needed to raise enough seedlings for planting one hectare. For nursery raising, beds measuring about 2 m × 1 m are commonly used. The beds should be well prepared and free from clods. About 10 kg of well-decomposed farmyard manure (FYM) should be thoroughly incorporated into each nursery bed. Seeds can be sown at a rate of approximately 1 g per square metre.

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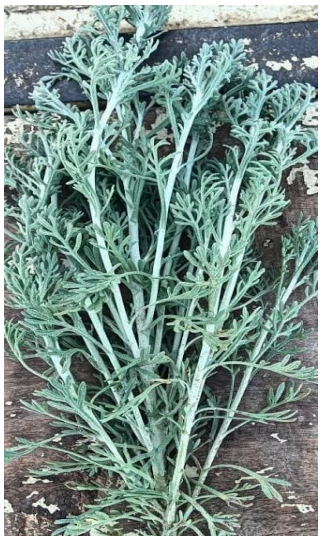
One method of sowing involves mixing the seeds thoroughly with clean sand at 4–5 times the volume of the seeds. Water is added to moisten the sand adequately, after which the mixture is placed in a cloth bag and kept in a warm location for about 48 hours. The nursery bed is then flooded with water to form a shallow pool, and the sprouted seed–sand mixture is broadcast evenly over the entire bed. This method promotes uniform seed distribution and helps achieve better germination. Seeds generally germinate within 2–3 days. The beds should be watered by hand until the seedlings become established, usually within 7–10 days, after which irrigation can be provided through the water channels.

Transplanting: Davana seedlings are generally ready for transplanting about 6–8 weeks after sowing, when they reach a height of approximately 10 cm. Before transplanting, the field should be thoroughly prepared by ploughing the soil several times until a fine tilth is obtained. The prepared field is then divided into convenient-sized plots using bunds and irrigation channels. This layout makes irrigation, weeding, and other intercultural operations easier. After the plots are prepared, about 6 tonnes of well-decomposed FYM or compost per hectare should be thoroughly incorporated into the soil. The plots should be irrigated one day before transplanting to provide adequate moisture for the seedlings. The seedlings are then carefully transplanted at a spacing of 15 x 7.5 cm. Studies have shown that closer spacing generally produces higher herbage and essential oil yields per unit area. Although wider spacing allows the plants to grow larger, it tends to result in lower overall herbage and oil production. Therefore, maintaining an appropriate closer spacing is beneficial for achieving better yield in davana cultivation.

Manures and Fertilizers: Well decomposed FYM at the rate of 6t/ha is incorporated in to the soil at the time of land preparation. Subsequently, a fertilizer dose of 40kg P and 40kg K /ha is given at the time of transplanting. The N is applied at the rate of 120kg/ha in three equal split doses. The first dose is given at 10 days after transplanting and the subsequent two doses at 15 days intervals thereafter.

Irrigation: After transplanting, the plots are immediately provided with light irrigation. Later irrigation is provided Crop is irrigated once in four or five days depending on the weather conditions.

Interculture: The field is kept weed-free by regular weeding as and when required. In all about 2-3 hand weeding during the early period of growth will help to keep the weeds down.



Harvesting and yield: The plants become ready for cuttings in two and half months after transplanting. In order to obtain the maximum essential oil yield, the plants should be harvested when about 50% of them have come to the flowering stage, which will be around the 2nd or 3rd week of February. Subsequent cuttings are taken at 30 - 40 days intervals. This is usually at the end of February or in the 1st week of March, about 120-125 days after sowing. Oil recovery will be 0.13 % on 50th day and 0.23 % on the 75th day.

The yield of fresh herbage, including flower-heads, is around 12-13 t/ha. Though, under laboratory conditions, the oil content in the whole plant

after during it in the shade for 2 days is 0.29%. An average recovery of around 0.2% under large-scale distillation, yielding 12-13 kg/ha of oil may be considered satisfactory.

Pest and Diseases: No serious attack of insect pests has been reported in davana. However, some insect pests like leaf eating caterpillars, aphids and termites have been observed to affect the crop, while the spraying of any systemic insecticide like 0.05% of Monocrotophos or 0.2% of Dimethoate will control the incidence of aphids and the spraying of contact insecticides like 0.2% Metacid will control leaf eating caterpillars.

Damping off- The disease is caused by fungus belonging to the Rhizoctonia spp. It is usually severe at the nursery stage. Controlling the irrigation will reduce the incidence of the disease. Treating the seeds with Emisan @ 0.2% before sowing and then drenching the seed beds with the above chemicals a week after germination controls the disease.

Conclusion

Davana (*Artemisia pallens* Wall.) is a commercially important aromatic crop with considerable potential for essential oil production, floricultural uses and value-added products. Successful cultivation depends on the use of fresh, viable seed, proper nursery management, timely transplanting, adequate nutrient and irrigation management, and effective weed control. Harvesting at approximately 50 per cent flowering is particularly important for obtaining better essential oil yield and quality. With its distinctive fragrance, established demand in domestic and international markets, and applications in perfumes, cosmetics, flavouring and religious offerings, systematic cultivation and improved production practices can enhance the productivity and profitability of davana cultivation.

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DIGITAL FISHERIES: HOW DRONES, SATELLITES, AND AI ARE CHANGING FISHERY MANAGEMENT

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Abstract

Digital technologies are transforming the way fisheries are monitored, studied, and managed. Drones, satellites, and artificial intelligence (AI) are increasingly being used to collect information about fishing activities, aquatic habitats, vessel movements, and environmental conditions. Drones provide high-resolution observations of coastal and inland waters, while satellites offer broad-scale monitoring of oceans and remote fishing grounds. AI and machine-learning algorithms help process large volumes of data, identify fishing patterns, detect vessels, and support decision-making. These technologies can improve fisheries surveillance, stock assessment, habitat conservation, and the management of illegal, unreported, and unregulated (IUU) fishing. However, challenges such as data gaps, technical costs, limited expertise, and unequal access remain important. This article discusses the applications, benefits, and limitations of digital fisheries technologies and their potential to support more sustainable and transparent fisheries management.

Keywords: Digital fisheries, satellite remote sensing, fisheries management, IUU fishing.

Introduction

Fisheries play an important role in food security, employment, livelihoods, and economic development. However, overfishing, habitat degradation, climate change, and illegal, unreported, and unregulated (IUU) fishing create serious challenges for sustainable fisheries management. Traditional monitoring methods, such as field surveys, landing-site observations, logbooks, observer programmes, and patrol vessels, remain essential, but they may be costly, time-consuming, and limited in geographic coverage. The need for accurate, timely, and large-scale information has encouraged the adoption of digital technologies in fisheries science and governance (Bradley *et al*., 2019).Digital fisheries refers to the use of modern technologies—including satellite remote sensing, drones, vessel-tracking systems, electronic monitoring, cloud computing, and artificial intelligence—to collect, analyse, and apply fisheries-related information. These technologies can help managers understand fishing patterns, monitor environmental changes, identify potentially suspicious activities, and improve the scientific basis of management decisions. The integration of satellite data and machine learning has already made it possible to map fishing activity across large ocean regions, demonstrating the potential of digital tools to improve transparency in fisheries (Kroodsma *et al*., 2018).The use of digital technologies is not intended to replace conventional fisheries science. Instead, these tools complement biological sampling, catch statistics, field observations, and the knowledge of fishing communities. Their effectiveness depends on reliable data, appropriate interpretation, institutional capacity, and responsible governance. Therefore, digital fisheries should be viewed as an integrated approach that combines technology with scientific knowledge and stakeholder participation (Bradley *et al.,* 2019).

Drones: High-Resolution Eyes Over Aquatic Ecosystems

Drones, also known as unmanned aerial vehicles (UAVs), are becoming useful tools for monitoring coastal waters, rivers, lakes, wetlands, and aquaculture systems. Equipped with cameras and other sensors, drones can capture high-resolution images of aquatic environments and provide information that may be difficult to obtain through conventional surveys. In fisheries management, drones can support habitat mapping, observe shallow-water ecosystems, monitor fishing activities, document changes in coastal areas, and assist in the assessment of fishery resources. Their flexibility and ability to survey specific locations make them particularly useful for localized monitoring and rapid environmental assessments (Toonen & Bush, 2020). Drones can also contribute to fisheries surveillance by providing aerial observations of boats, fishing gear, and activities in coastal waters. Compared with some conventional surveillance methods, they may offer a relatively flexible and economical option for monitoring selected areas. However, their usefulness depends on flight regulations, weather conditions, battery life, operator expertise, and the ability to interpret aerial images accurately. Drone observations should therefore be combined with field verification and other monitoring systems rather than being treated as a complete replacement for established fisheries-surveillance methods (Food and Agriculture Organization of the United Nations [FAO], 2022; Toonen & Bush, 2020).

Satellites: Monitoring Fisheries Across Large and Remote Areas

Satellite remote sensing provides a broad view of oceans and inland waters, making it valuable for monitoring environmental conditions and fishing activities over large geographic areas. Satellite imagery can be used to observe sea-surface temperature, chlorophyll concentration, ocean colour, habitat characteristics, and coastal changes. These environmental variables are important because they influence primary productivity, fish distribution, and the functioning of aquatic ecosystems. Satellite-derived information can therefore support habitat studies, fishery forecasting, and the identification of areas requiring further investigation (Butler *et al.,* 1988). Satellites are also increasingly important in vessel monitoring and fisheries surveillance. Automatic Identification System (AIS) data provide information about the movements of vessels that transmit their positions, while satellite imagery can help identify vessels and activities that may not be visible through tracking data alone. In a global study, Kroodsma *et al.* (2018) used vessel-tracking data and machine-learning methods to map the spatial and temporal footprint of industrial fishing worldwide. Such systems can improve understanding of fishing effort and support monitoring, control, and surveillance activities. Satellites: Monitoring Fisheries Across Large and Remote Areas.

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worldwide. Such systems can improve understanding of fishing effort and support monitoring, control, and surveillance activities.

However, satellite monitoring has limitations. Optical imagery may be affected by cloud cover, while the detection of small vessels and certain fishing activities can be difficult. AIS data also do not represent every fishing vessel, particularly where vessels do not carry or transmit AIS. Consequently, satellite-based observations should be interpreted carefully and combined with other data sources, including VMS, logbooks, observer information, and field surveys (FAO, 2022; Kroodsma *et al*., 2018).

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Artificial Intelligence: Converting Data into Fisheries Intelligence

Satellites and drones generate large quantities of images and observations, but these data must be processed before they can support fisheries management. Artificial intelligence, particularly machine learning and computer vision, helps convert complex datasets into useful information. AI models can analyse vessel movements, classify objects in images, identify patterns associated with fishing activity, estimate environmental conditions, and support fisheries monitoring and assessment. These applications can reduce the time required for processing large datasets and help managers examine information at broader spatial and temporal scales (Bradley *et al*., 2019).

One important application is the identification of apparent fishing activity from vessel-tracking data. Kroodsma *et al*. (2018) developed a machine-learning approach to analyse global vessel movements and identify patterns associated with fishing. Such systems can help reveal fishing activity across large ocean areas and improve the availability of information for researchers, managers, and other stakeholders. AI may also support fish identification, automated fish counting, catch estimation, stock assessment, and the prediction of fish distribution when suitable training data are available (Bradley *et al*., 2019). Despite its potential, AI is not error-free. Its results depend on the quality and representativeness of training data, the design of algorithms, and the conditions under which the models are applied. A system may misclassify vessel movements or confuse fishing-related activity with other maritime activities. Therefore, AI-generated results should be validated using expert knowledge, field observations, and independent datasets. Transparency, responsible data use, and human oversight are essential for ensuring that digital fisheries technologies support sound management decisions (Bradley *et al.,* 2019; FAO, 2022).

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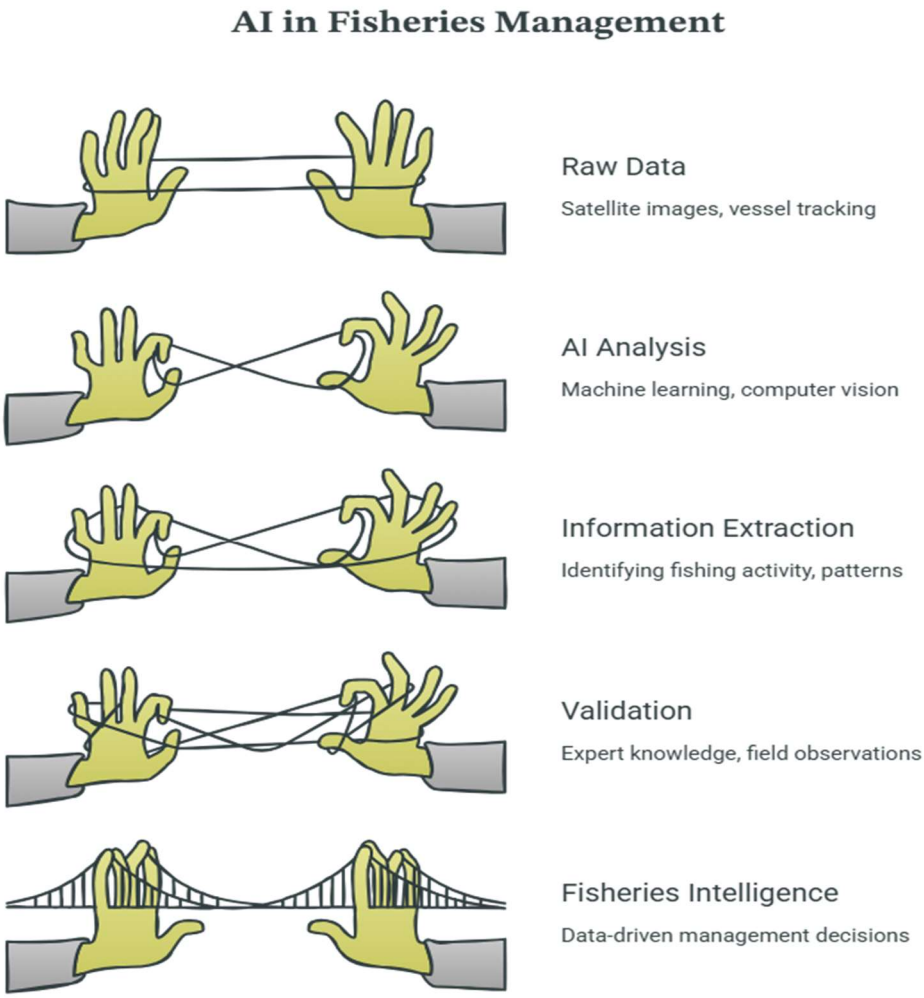


Fig1: AI in Fisheries Management

Conclusion

Digital fisheries technologies are creating new opportunities to improve the monitoring, assessment, and management of aquatic resources. Drones provide detailed local observations, satellites offer broad-scale environmental and vessel monitoring, and artificial intelligence helps transform complex datasets into useful information for decision-making. Together, these technologies can strengthen fisheries surveillance, support habitat conservation, improve stock assessment, and contribute to the detection of potentially illegal fishing activities.However, technology alone cannot solve every fisheries management problem. Effective implementation requires reliable data, trained personnel, suitable infrastructure, transparent governance, and cooperation among scientists, government agencies, fishing communities, and other stakeholders. Small-scale fishers should not be excluded because of unequal access to digital tools or concerns about data ownership and privacy. Digital technologies should therefore be used as complementary tools alongside conventional fisheries science and local knowledge. When applied responsibly, they can contribute to more informed, transparent, and sustainable fisheries management.

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DIGITAL TECHNOLOGIES IN FISHERIES RESOURCE MANAGEMENT: FROM REMOTE SENSING TO ARTIFICIAL INTELLIGENCE

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Introduction

Fisheries and aquaculture are essential for food security, livelihoods, and sustainable utilization of aquatic resources, but climate change, biodiversity loss, overfishing, and increasing seafood demand are creating major challenges for effective resource management. Conventional monitoring approaches are often labour-intensive, costly, and limited in spatial and temporal coverage, highlighting the need for more efficient digital solutions. Remote sensing and satellite-based technologies provide opportunities for large-scale monitoring of aquatic environments, habitat conditions, and fishing activities, while sensor networks, underwater imaging, and acoustic systems generate detailed biological and environmental information. Environmental DNA (eDNA) further supports sensitive and non-invasive monitoring of aquatic biodiversity. The rapid development of artificial intelligence (AI), particularly machine learning and deep learning, enables automated analysis of large and complex fisheries datasets and improves fish detection, species identification, abundance estimation, and forecasting (Haque *et al*., 2026). Integration of AI with remote sensing, acoustic, imaging, vessel-monitoring, and environmental datasets can strengthen real-time monitoring and evidence-based decision-making. However, challenges related to data quality, standardization, model transferability, uncertainty, and technological accessibility remain important. Therefore, combining digital technologies with established fisheries management practices is essential for developing sustainable, resilient, and transparent approaches to fisheries resource management.

Remote sensing and spatial technologies in fisheries resource management

Remote sensing

Remote sensing technologies, particularly satellite-based observations, provide large-scale and repeated information on aquatic environments and fisheries-related habitats. Satellite sensors can monitor parameters such as sea surface temperature, chlorophyll-a concentration, turbidity, ocean colour, water extent, and changes in coastal and inland aquatic habitats. These observations help identify productive fishing areas, assess habitat conditions, monitor environmental changes, and support fisheries resource assessment. Remote sensing also enables monitoring over large and remote areas where conventional field surveys are difficult or costly. Integration of satellite observations with fisheries catch, oceanographic, and environmental datasets can improve resource assessment and management decisions.

GIS and spatial analysis

Geographic Information Systems (GIS) provide a framework for storing, integrating, analysing, and visualizing spatial information related to fisheries and aquatic ecosystems. GIS can combine satellite

imagery with information on fish distribution, fishing grounds, habitat characteristics, water quality, bathymetry, and environmental variables to identify spatial patterns and potential fishing areas. Spatial analysis can support habitat suitability assessment, identification of critical fish habitats, mapping of aquaculture sites, and evaluation of changes in aquatic ecosystems. GIS-based decision-support systems therefore help managers interpret complex spatial information and develop more targeted fisheries management strategies (Dineshbabu *et al*., 2016).

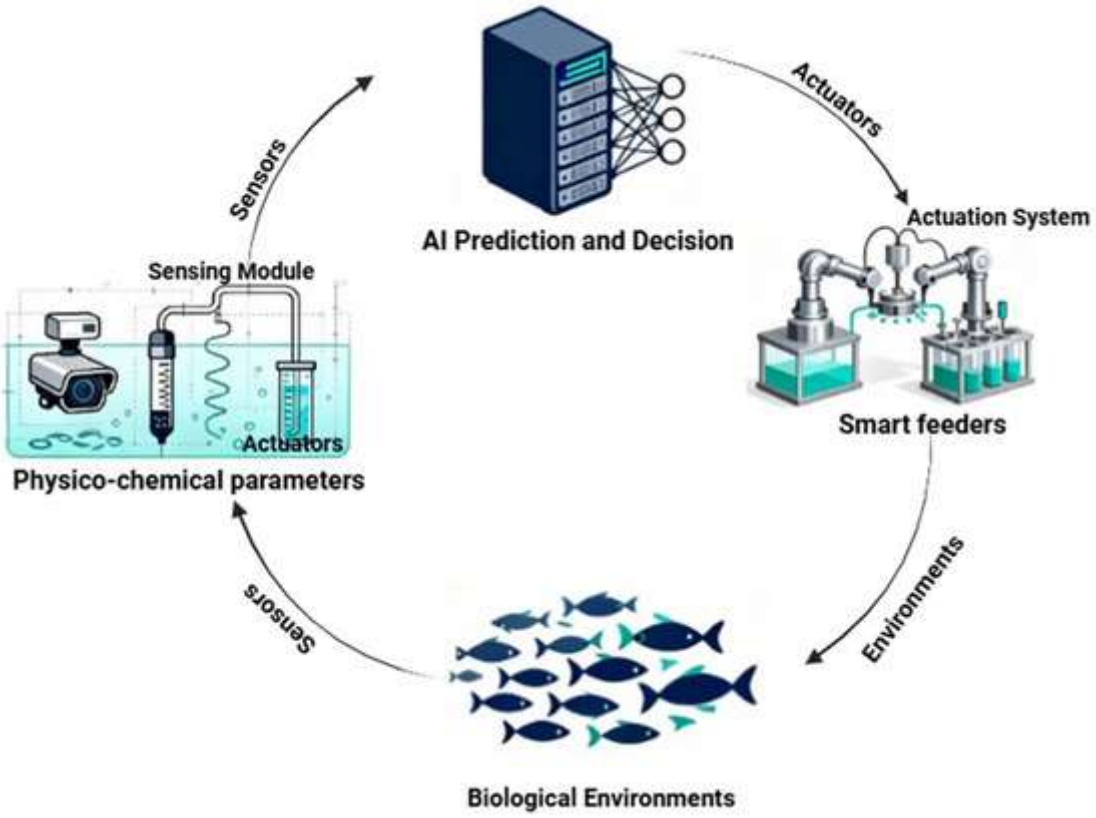


Figure 1. AI-Enabled Aquaculture Control Loop.

Satellite-based fisheries monitoring

Satellite-based monitoring supports fisheries management by providing information on fishing activity, vessel location, environmental conditions, and changes in fishing grounds. Satellite Automatic Identification System (AIS), Vessel Monitoring Systems (VMS), and satellite imagery can be used to track vessel movements and identify fishing patterns, while remote-sensing data can help relate fishing activity to oceanographic conditions. Combining vessel-tracking information with catch data and environmental observations can improve monitoring of fishing pressure, support compliance and surveillance, and assist in identifying potentially important fishing areas. These technologies provide a scalable approach for monitoring fisheries over large marine areas and can complement conventional vessel-based surveys.

AI in fisheries genetics and monitoring

Artificial intelligence (AI) and advanced digital technologies are transforming fisheries genetics and population monitoring by integrating computer vision, acoustic sensing, environmental DNA (eDNA), genomics, and statistical modelling. Computer vision enables automated detection, classification, and tracking of fish under complex underwater conditions, although turbidity, variable

illumination, seasonal changes, and rare species can reduce detection accuracy. Transfer learning and domain-adaptation techniques can improve the performance of models across different habitats and seasons, while image-enhancement methods can support the analysis of low-resolution and noisy underwater images. However, enhancement methods must be carefully validated because artificial image details may affect biological measurements such as fish abundance and body length. eDNA metabarcoding provides a sensitive and non-invasive approach for detecting species and monitoring changes in aquatic communities, complementing conventional fisheries surveys. Acoustic techniques further provide information on fish distribution and biomass, and their integration with underwater imagery and eDNA can improve ecosystem-level monitoring. Population genomics and multi-omics approaches provide information on stock structure, genetic connectivity, local adaptation, and population dynamics, while genome-editing technologies such as CRISPR/Cas are being investigated for improving important aquaculture traits. In addition, trait-based indicators and mixed-effects statistical models help relate biological characteristics such as growth, maturation, and longevity to fishing pressure and environmental variability. The integration of visual, acoustic, molecular, genomic, and statistical information therefore provides a framework for continuous, non-invasive, and data-driven fisheries monitoring.

Species detection and classification

Modern convolutional neural networks and object-detection models have improved the automated identification and classification of fish species in underwater images. However, their performance can decline under turbidity, variable illumination, seasonal changes, occlusion, and habitat shifts, particularly for rare and protected species. Underwater-specific architectures, stereo imaging, and multi-fish tracking can improve detection and reduce duplicate counting. Large and diverse image datasets representing different habitats, life stages, species, and environmental conditions are essential for developing robust models. Therefore, model performance should be reported together with dataset size, class distribution, habitat coverage, and detection performance for rare or difficult-to-detect species.

Transfer learning and domain adaptation

Transfer learning using pre-trained convolutional neural networks can reduce the requirement for large labelled datasets when models are applied to new habitats. However, differences in water colour, illumination, turbidity, backscatter, season, and camera systems can reduce model generalization. Domain-adaptation approaches, underwater-specific detector architectures, and video-based processing can improve consistency across locations and seasons. Stereo-video datasets, active learning, and disagreement-based annotation can further reduce the amount of manual labelling required. Multi-regional datasets that include rare, protected, and low-abundance species are particularly important for reducing bias in automated fisheries monitoring.

Low-resolution and noisy image handling

Underwater images are frequently affected by low resolution, turbidity, backscatter, poor illumination, and image degradation. Super-resolution techniques can improve the visual quality of such images, but excessive enhancement may generate artificial features that influence measurements of fish size, abundance, or species identity. Task-specific approaches that combine image enhancement with downstream detection models can improve recognition while reducing false detections. Such methods should be validated against original high-quality observations and tested under realistic environmental conditions before being applied to fisheries assessment.

Environmental DNA monitoring

Environmental DNA (eDNA) metabarcoding provides a non-invasive approach for detecting aquatic species and characterizing community composition. It can complement conventional netting, visual surveys, and other fisheries-monitoring methods, particularly when species are rare, cryptic, or difficult to capture. However, eDNA concentration does not always directly represent organism abundance because DNA transport, degradation, water movement, and sampling conditions can influence detection. Standardized field and laboratory controls, including field blanks and molecular validation using qPCR or digital PCR, are therefore important. Improved reference sequence libraries are also required for reliable identification, particularly for poorly studied aquatic fauna.

Acoustic inference and multi-sensor fusion

AI-based fisheries acoustics can automate the classification of acoustic signals and support the estimation of fish distribution and biomass. Acoustic observations provide information that complements underwater imagery, while synchronized video and acoustic systems can improve species identification and biodiversity assessment. Integrating acoustic, visual, and eDNA observations through time-aligned multi-sensor frameworks can provide a more comprehensive representation of fish communities. Incorporating uncertainty into these systems is essential for producing reliable information for fisheries management and ecosystem assessment.

Genomics and breeding technologies

Population genomics and multi-omics approaches provide valuable information on genetic diversity, stock structure, population connectivity, and local adaptation. Their application is particularly useful for distinguishing genetically differentiated populations and improving understanding of population dynamics. However, genomic resources remain unevenly developed among economically and ecologically important fish species. Genome-editing technologies such as CRISPR/Cas are also being investigated for improving disease resistance, growth, and other production traits in aquaculture. Future applications require reliable reference genomes, standardized genomic datasets, appropriate biosafety frameworks, and collaboration among geneticists, aquaculture researchers, fisheries managers, and policymakers.

Trait-based and statistical modelling approaches

Trait-based approaches and hierarchical statistical models can connect biological characteristics such as growth, maturation, fecundity, and longevity with fishing pressure and environmental variability. Generalized linear mixed models (GLMMs) and linear mixed-effects models (LMEMs) can account for variation among individuals, populations, sampling locations, and environmental conditions. These approaches can improve interpretation of community-level changes and support fisheries forecasting. However, differences in trait databases among species and geographical regions can limit comparability. Expanding standardized trait datasets and integrating biological traits with genetic, acoustic, imaging, and environmental information can strengthen population-level assessment and prediction.

AI in aquaculture

Artificial intelligence (AI) is transforming aquaculture from reactive farm management towards adaptive and data-driven production systems. AI integrates real-time information from feeding systems, water-quality sensors, cameras, environmental data, and farm records to support decisions related to feed management, animal welfare, disease detection, water quality, growth, and harvesting. Automated feeding systems can estimate appetite and biomass, helping to reduce feed

wastage and improve feed conversion efficiency. Machine-learning models can combine feeding history, growth patterns, and environmental conditions to optimize feeding strategies, whereas reinforcement-learning approaches are being investigated for simultaneous control of feeding and water-quality parameters in recirculating aquaculture systems. Computer vision provides opportunities for continuous monitoring of fish behaviour, welfare, biomass, and disease symptoms. AI-based forecasting can predict dissolved oxygen, ammonia, growth, and harvest timing, allowing farmers to take preventive actions before adverse conditions develop. Emerging applications include climate-scenario simulation, explainable AI (XAI), biofloc optimization, and Artificial Intelligence of Things (AIoT). However, differences between experimental validation and actual farm performance remain an important challenge. Therefore, uncertainty quantification, multi-season validation, standardized datasets, and farmer- or manager-in-the-loop testing are essential for translating AI prototypes into reliable aquaculture decision-support systems.

Automated feeding systems

AI-enabled feeding systems combine computer vision, machine learning, and temporal models to estimate fish biomass, feeding activity, and short-term feed demand. Convolutional neural networks (CNNs) and recurrent models such as gated recurrent units (GRUs) can assist in predicting feeding requirements and improving feed conversion efficiency. However, many studies have been conducted under controlled tank conditions and for individual species, limiting their direct application to commercial ponds, cages, and mixed-size populations. Vision-based biomass estimation combined with continuously updated temporal models can adjust feeding decisions according to biomass, season, and environmental conditions. Integration with real-time water-quality forecasts can further reduce feeding during periods when oxygen demand may increase the risk of post-feeding hypoxia. Future studies should evaluate these systems across multiple farms and seasons while considering turbidity, low-light conditions, model drift, and overall economic benefits.

Machine learning for feeding optimization

Supervised machine-learning methods, including gradient boosting, support vector regression, and ensemble models, can optimize feed ration by integrating appetite indicators, growth history, stocking information, and environmental variables. However, models trained using data from a single farm may perform poorly when applied to farms with different stocking densities, sensor configurations, feed formulations, or management practices. Reliable deployment therefore requires sensor-quality control, appropriate treatment of missing data, regular model retraining, and testing under changing environmental conditions. Uncertainty-aware systems can reduce or modify feeding recommendations when prediction confidence decreases. Development of shared and anonymized multi-farm datasets would improve model comparison and help evaluate both production outcomes and environmental indicators such as nutrient discharge (Saad *et al*., 2024).

Reinforcement learning controllers

Reinforcement learning (RL) is being investigated for controlling complex aquaculture operations, particularly in recirculating aquaculture systems (RAS). These approaches can optimize feeding, aeration, water exchange, and other operational parameters under changing environmental conditions. However, RL models require substantial training data, and inappropriate reward functions may result in undesirable management decisions. Rare but serious events, such as aeration or equipment failure, also require robust safety constraints. Offline training using Supervisory Control and Data Acquisition (SCADA) records, action constraints, physics-informed

models, and safety rules can improve the reliability of RL controllers. Comparative evaluation against established Model Predictive Control (MPC) systems under identical RAS conditions is important for assessing practical performance, animal welfare, and energy consumption.

Water quality forecasting

AI-based forecasting of water-quality parameters can provide early warnings of potentially harmful conditions in aquaculture systems. Deep-learning models using Internet of Things (IoT) sensor data can forecast dissolved oxygen, pH, ammonia, and related parameters several hours in advance (Pandey *et al*., 2026). Such predictions can support proactive aeration, water exchange, and other management interventions. However, sensor fouling, missing observations, changes in biomass, temperature variation, and concept drift can reduce prediction accuracy. Effective systems should therefore include automated data-quality checks, missing-data handling, drift detection, and uncertainty estimation. Multi-season validation of simultaneous dissolved oxygen and nitrogenous waste predictions can further improve the reliability of AI-based water-quality management.

Welfare and stress monitoring

Computer vision is increasingly being used to monitor fish behaviour as an indicator of welfare and stress. Changes such as abnormal swimming, excessive clustering, reduced activity, or altered movement patterns can provide early indications of environmental or health-related problems. However, visibility, stocking density, turbidity, and limited commercial-farm datasets can affect model performance. Combining video monitoring with multi-object tracking and environmental sensors can provide a more comprehensive assessment of fish condition. AI-based disease-detection systems can also identify visible lesions and other external symptoms, but their effectiveness depends strongly on the availability of high-quality, expert-labelled images. Future research should focus on standardized welfare datasets and evaluate AI systems based on practical outcomes such as early intervention, reduced mortality, and improved animal welfare.

Harvest forecasting and planning

AI-based time-series models can combine growth records, feeding history, environmental conditions, and market information to support harvest planning. Such systems can estimate growth trajectories and identify potential harvest periods while considering changes in product quality, weather, and market conditions. However, many existing studies rely on retrospective datasets and provide limited information about prediction uncertainty. Integrating growth ensembles with digital-twin platforms can allow farmers to compare alternative harvest dates and visualize confidence intervals. Continuous updating with actual grading and harvest data can further improve model accuracy. Prospective farm trials comparing AI-supported decisions with conventional management practices are necessary to determine their practical value (Ugwu *et al*., 2025).

Conclusion

Digital technologies are transforming fisheries and aquaculture resource management by enabling more efficient, timely, and data-driven monitoring and decision-making. Remote sensing, GIS, satellite-based monitoring, IoT sensors, underwater imaging, acoustic systems, and environmental DNA provide complementary information on aquatic environments, fish populations, habitats, and fishing activities. The integration of these technologies with artificial intelligence, machine learning, computer vision, genomics, and predictive modelling further strengthens species identification, biomass estimation, environmental forecasting, feeding management, disease detection, welfare monitoring, and harvest planning. However, limitations related to data quality, model transferability,

infrastructure, standardization, uncertainty, and accessibility must be addressed before widespread adoption. Future efforts should focus on multi-source data integration, standardized datasets, real-world validation, explainable and uncertainty-aware AI, and affordable digital solutions for different scales of fisheries and aquaculture. Thus, combining digital technologies with conventional scientific knowledge and fisheries management practices can support sustainable, resilient, and evidence-based management of aquatic resources.

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ECOPATH MODELLING FOR AQUATIC FOOD-WEB ANALYSIS AND ECOSYSTEM MANAGEMENT

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Introduction: Why Food Webs Matter

Every lake, estuary, coral reef, and ocean basin runs on the same basic currency: energy captured by photosynthesis (or, in the deep sea, by chemosynthesis) and transferred from one organism to another through feeding. A single fish species rarely lives or dies in isolation. Its abundance is tied to the phytoplankton at the base of the system, the zooplankton and forage fish it consumes, the predators that eat it, and the fisheries that harvest it. When managers regulate a single stock without understanding these connections, they risk unintended consequences: removing too many sardines can starve seabirds and tuna; protecting a predator too effectively can crash the very prey stocks fishers depend on. This interconnectedness is why ecosystem-based approaches to fisheries and conservation management have become central to modern marine and freshwater science. Rather than modeling one species in isolation, ecosystem modeling asks: how does energy flow through the entire food web, and what happens when we perturb one part of it? Among the tools developed to answer this question, few have been as widely adopted, tested, and refined as Ecopath mass-balancing modeling.

What Is Ecopath and What Does It Do?

Ecopath is a mass-balance modeling approach that reconstructs the flow of biomass and energy among the functional groups of an aquatic ecosystem — from primary producers and detritus to top predators and fisheries — at a defined point in time. Jeffrey Polovina originally developed it in the early 1980s to describe an idealized coral reef ecosystem, using linked equations to balance production against consumption, growth, and mortality across all system components (Polovina, 1984). Villy Christensen and Daniel Pauly later reformulated and popularized the model, reframing its energy-balance logic around ecotrophic efficiency and pairing it with a growing software platform, Ecopath with Ecosim (EwE). This platform is now maintained and distributed as a free scientific tool used in hundreds of published ecosystem studies worldwide (Christensen and Pauly, 1992; Christensen and Walters, 2004). At its core, Ecopath produces a static "snapshot" of an ecosystem: a quantified picture of how much biomass exists in each group, how fast that biomass is produced and consumed, and how energy is partitioned among predation, fisheries catch, and other losses. This snapshot forms the foundation for more dynamic simulations (Ecosim) and spatial applications (Ecospace), but even on its own, an Ecopath model is a powerful diagnostic and management tool.

From Diets to Diagrams: Building Food-Web Structure

Constructing an Ecopath model begins by defining the ecosystem's functional groups — clusters of species (or single key species) that share similar ecological roles, prey, and predators. A coastal shelf

model, for instance, might include groups such as phytoplankton, benthic algae, zooplankton, benthic invertebrates, small pelagic fish, demersal fish, sharks, seabirds, and marine mammals, plus a "detritus" pool that recycles dead organic matter back into the system. Once these groups are defined, the modeller assembles a diet-composition matrix that specifies the proportion of each predator's diet derived from each prey group. This matrix, combined with biomass and production data, allows Ecopath to reconstruct the entire network of feeding relationships — effectively mapping "who eats whom, and how much" across the ecosystem. The result is often visualized as a flow diagram in which functional groups are arranged vertically by trophic level and connected by arrows that indicate the direction and magnitude of energy transfer.

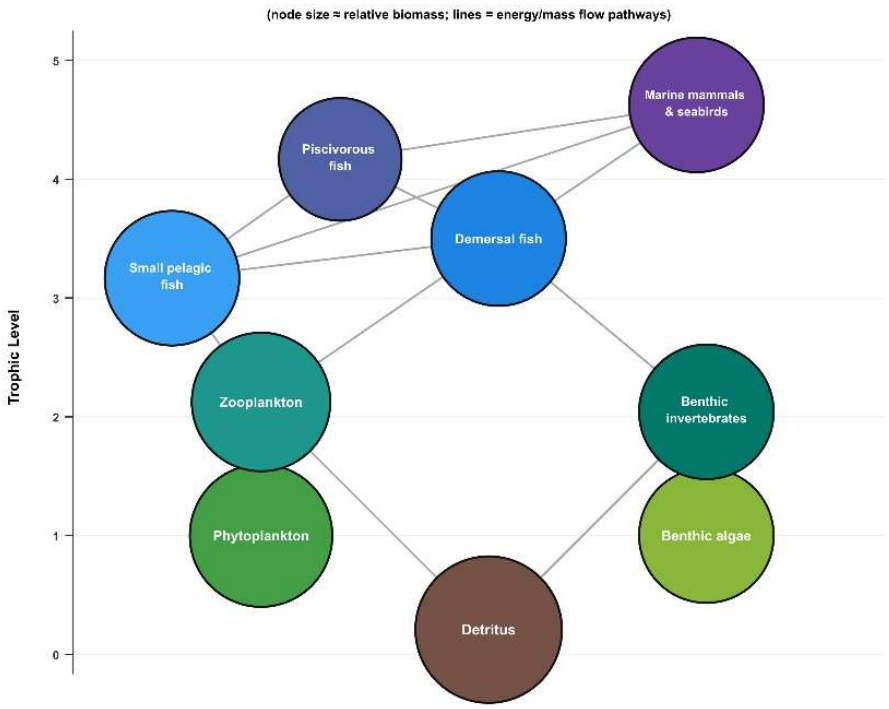


Figure 1. A simplified Ecopath-style flow diagram. Functional groups are positioned by estimated trophic level, node size is proportional to relative biomass, and arrows indicate the direction of mass/energy flow from prey to predator. Real Ecopath models typically include 20–60+ functional groups.

Core Inputs for Ecopath Models

Every Ecopath model is built from four basic parameters for each functional group, at least three of which the user must supply (the model can estimate the fourth). Groups are defined by ecological similarity rather than taxonomy alone — a "small pelagic fish" group might combine several species of sardine, anchovy, and herring that occupy a similar trophic niche, while a keystone or heavily fished species may be isolated as a single-species group so its dynamics can be tracked individually. The standing stock of each group is usually expressed as tonnes per square kilometer (wet weight). Estimates come from fisheries-independent surveys (trawl, acoustic, or visual census), catch-per-unit-effort data, or literature values from comparable systems. The production-to-biomass ratio (P/B) approximates the total mortality rate for many exploited populations. In contrast, the

consumption-to-biomass ratio (Q/B) describes how much food a group consumes relative to its biomass. Fisheries catch is partitioned among fleets and gear types, and additional "other mortality" terms can capture disease, non-predatory natural mortality, or emigration. Data for these inputs are drawn from a wide range of sources: stock assessments, scientific surveys, stomach-content and stable-isotope studies, landings statistics, and the FishBase (https://www.fishbase.se/search.php) and SeaLifeBase (https://www.sealifebase.ca/) databases, which provide standardized life-history parameters for thousands of species (Froese and Pauly, 2023).

How Ecopath Works: The Logic Behind the Model

Ecopath's mathematical foundation is a deceptively simple mass-balance equation applied to each functional group. In essence, a group's production must equal the sum of all losses from that group: fisheries catch, predation mortality, net migration, biomass accumulation, and other mortality. Because this equation is written for every group simultaneously, the whole system becomes a set of linear equations that must all balance at once — which is why the approach is called mass-balance modeling. Solving this system tells the modeler, for each group, whether the estimated production is sufficient to cover all the demands placed on it (fishing, predation, and export) or whether the inputs are ecologically inconsistent. A key diagnostic is Ecotrophic Efficiency (EE), the proportion of a group's production consumed within the system or removed by fishing. EE values greater than 1.0 are biologically impossible and signal that one or more inputs need revision.

Model Calibration and Balancing

A modeler's first-pass input estimates rarely balance perfectly. Ecopath flags any functional group whose EE exceeds 1.0. Balancing a model is as much a craft as a calculation: modelers adjust uncertain parameters within plausible ranges, cross-check against independent data sources, and use sensitivity routines (such as PREBAL diagnostics and Monte Carlo-based uncertainty tools) to identify which inputs most strongly affect model stability (Link, 2010; Heymans *et al*., 2016). A well-balanced model is not necessarily "correct" — it is one whose energy budget is at least internally consistent and biologically plausible, providing a defensible starting point for further analysis.

Ecological Indicators You Can Extract

Once balanced, an Ecopath model yields a rich set of synthetic descriptors of ecosystem structure and function. It calculates the trophic level of every group (including mixed-diet consumers) and aggregates flows into discrete trophic levels to show how efficiently energy is transferred up the food web. Ecopath also computes total system throughput, mean transfer efficiency between trophic levels (classically approximated at 10%, though empirical values vary), and the relative importance of the grazing versus detrital energy pathways.

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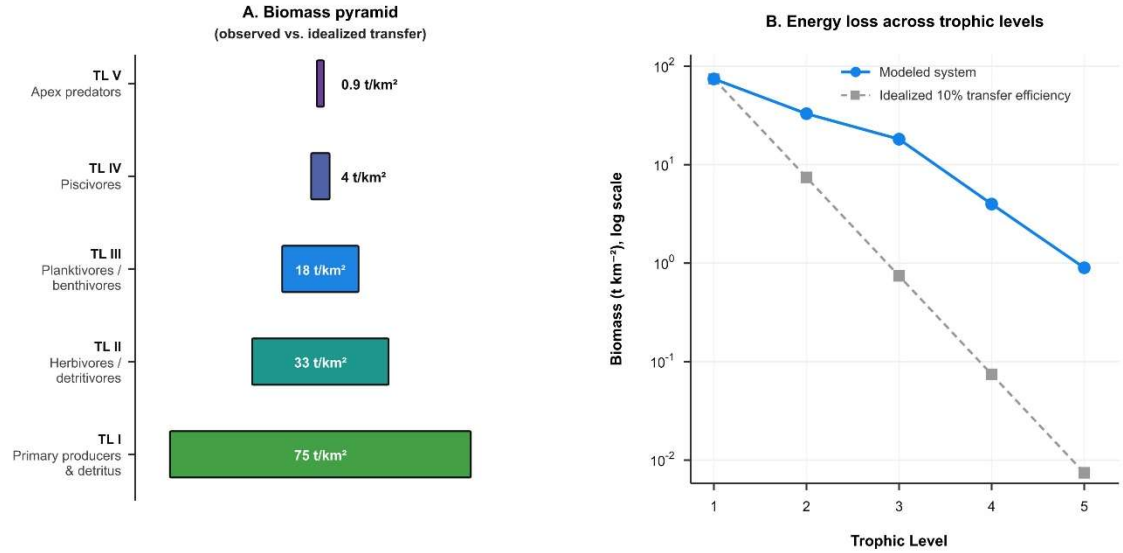


Figure 2(A). A biomass pyramid showing the typical decline in standing stock from primary producers to apex predators. (B). The same data on a logarithmic scale, compared with an idealized 10% trophic transfer efficiency, illustrating how real systems can retain more (or less) energy at upper levels than the classical "rule of thumb" predicts.

Metrics such as the predator-to-prey biomass ratio, keystoneness indices (Libralato *et al*., 2006), and mixed trophic impact (MTI) analysis identify which groups exert disproportionate top-down or bottom-up control over the rest of the system. Drawing on theories of ecosystem development advanced by Ramon Margalef and Eugene Odum, Ecopath also computes indices such as the Finn cycling index, connectance index, and Ulanowicz's system ascendency/overhead ratio, which are often interpreted as proxies for ecosystem maturity, internal organization, and resilience to perturbation (Odum, 1969; Ulanowicz, 1986; Christensen and Pauly, 1993).

Assessing Ecosystem Status and Management Scenarios

Because an Ecopath model captures the full network of biomass flows, it serves as a testbed for exploring "what-if" questions that single-species stock assessments cannot address alone. Modelers can assess how much of each group's production is currently extracted by fisheries relative to its ecological role, identify groups approaching or exceeding sustainable exploitation, and estimate the ecosystem-wide footprint of specific fleets or gear types. By comparing balanced models across time periods, researchers can track shifts in biomass, trophic structure, and energy pathways following overfishing, protection measures, or the establishment of invasive species — a technique widely used to document "fishing down marine food webs," in which the mean trophic level of catches declines over time as top predators are depleted (Pauly *et al*., 1998).

Linking to Ecological Dynamics

Ecopath itself does not simulate change over time—it describes a single balanced state. To explore trajectories, scenarios, and management strategies dynamically, practitioners typically move to Ecosim, which re-expresses Ecopath's balanced parameters as a system of coupled differential equations and simulates biomass changes over months to decades in response to fishing, climate forcing, or other drivers (Walters *et al*., 1997). For questions with an explicit spatial dimension—marine protected area design, spatial closures, or habitat-linked management—the Ecospace

module extends these dynamics across a gridded seascape (Walters *et al*., 1999; Christensen and Walters, 2004). Ecopath is therefore best understood as the essential first step: a rigorously balanced foundation on which the dynamic and spatial extensions cannot be reliably built.

Common Challenges and Sources of Uncertainty

No ecosystem model is free of uncertainty, and Ecopath's transparency about its assumptions is one of its strengths. Many ecosystems, especially in developing regions or in deep, remote habitats, lack long-term biomass or diet data for all functional groups, forcing modelers to borrow parameters from similar systems or rely on expert opinion. Some parameters — particularly diet composition and biomass of intermediate trophic-level groups — exert outsized influence on model outputs; small errors in these inputs can propagate into large uncertainties in derived indices (Essington, 2007). Ecopath assumes a static, "average annual" diet and a steady-state system, which may poorly represent ecosystems undergoing rapid change, strong seasonality, or ontogenetic diet shifts unless groups are split further by life stage. Aggregating species into functional groups can also mask important differences in vulnerability or role among the species lumped together (Fulton *et al*., 2003). Handled thoughtfully, however, these limitations are manageable: modern Ecopath practice includes formal uncertainty analysis, pedigree scoring of data quality, and sensitivity testing as standard components of model construction (Christensen *et al*., 2005; Heymans *et al*., 2016).

Case Studies and Real-World Applications

Ecopath models have now been developed for several hundred ecosystems worldwide, including coral reefs, temperate shelves, upwelling systems, estuaries, and freshwater lakes. Landmark applications include models of the Gulf of Alaska and Eastern Bering Sea, used to evaluate ecosystem-wide consequences of groundfish fisheries and inform ecosystem-based fishery management plans in U.S. federal waters (Aydin *et al*., 2007). In the Mediterranean Sea and the Northern Humboldt Current, models have quantified fishing impacts, identified keystone species, and evaluated the ecological consequences of small pelagic fish exploitation, which also supports seabirds and marine mammals (Tam *et al*., 2008; Coll *et al*., 2009).

Applications in the African Great Lakes (for example, Lake Victoria and Lake Malawi) have helped disentangle the combined effects of overfishing, invasive Nile perch, and eutrophication on native cichlid communities (Downing *et al*., 2014). On coral reefs, consistent with the model's original 1984 development, Ecopath continues to be used to explore the trophic consequences of coral bleaching, herbivore protection, and reef-fishery management. Collectively, these applications have shaped fisheries management advice, marine spatial planning, and conservation prioritization across dozens of countries. Ecopath outputs are now regularly incorporated into integrated ecosystem assessments conducted by agencies such as NOAA and ICES.

Best Practices for Using Ecopath in Management

Effective use of Ecopath in a management context generally follows several principles. Build functional group resolution around the specific management question rather than maximizing complexity for its own sake. Modelers should draw on the best available, most locally relevant data and document data quality using pedigree indices. Balancing adjustments must always be reported and interpreted transparently. Treat single Ecopath outputs as one line of evidence to be triangulated with single-species stock assessments and independent monitoring data, rather than as a stand-alone prediction. Finally, stakeholders and managers should be engaged early, since the

functional groupings and management scenarios examined should reflect real policy options under consideration (Plagányi, 2007; Heymans *et al*., 2016).

Conclusion: The Role of Ecopath in Ecosystem Management

More than four decades after its introduction, Ecopath remains one of the most widely used tools for translating the complexity of aquatic food webs into a structured, quantitative, and testable picture of ecosystem function. By forcing modelers to confront a system's full energy budget rather than a single species in isolation, it exposes ecological trade-offs—between fisheries and predators, between habitat change and food-web structure, and between short-term yield and long-term stability—that would otherwise remain hidden. Paired with its dynamic (Ecosim) and spatial (Ecospace) extensions, Ecopath forms the backbone of a modeling framework that continues to inform ecosystem-based fisheries management, marine protected area design, and conservation policy worldwide. Its enduring value lies not in providing a single "right answer," but in giving scientists and managers a transparent, shared framework for asking better questions about the ecosystems they are trying to sustain.

Glossary

Ecopath — A mass-balance software framework and modeling approach used to describe the flow of biomass and energy among functional groups in an aquatic ecosystem at a fixed point in time.

Ecosim — A dynamic simulation module built on a balanced Ecopath model, used to project ecosystem changes over time under fishing or environmental scenarios.

Ecospace — A spatial and temporal extension of Ecopath/Ecosim used to explore management scenarios (e.g., marine protected areas) across a mapped seascape.

Functional group — A set of species (or single species) grouped because they share a similar ecological role, diet, and predators within the model.

Biomass (B) — The total standing stock of a functional group, typically expressed as tonnes per square kilometer ($t \cdot km^{-2}$).

Production/Biomass ratio (P/B) — The rate at which a group produces new biomass relative to its standing stock; often approximates total mortality rate for exploited populations.

Consumption/Biomass ratio (Q/B) — The rate at which a group consumes food relative to its own biomass.

Ecotrophic Efficiency (EE) — The proportion of a group's production that predators, caught by fisheries, consume, or otherwise exported from the system (as opposed to dying of unexplained "other" mortality).

Diet composition matrix — A table specifying the proportion of each predator's diet contributed by each prey group in the model.

Trophic level (TL) — A measure of an organism's position in the food web, calculated from the trophic levels of its prey plus one.

Mixed trophic impact (MTI) — An analysis showing the direct and indirect effects that a change in one functional group's biomass would have on all other groups in the model.

Keystoneness — An index identifying species or groups whose ecological impact is disproportionately large relative to their biomass.

Mass-balance model — A model in which inputs and outputs for every component must sum consistently, so that no group is shown consuming or losing more biomass than the system actually produces.

Gross Efficiency (GE or P/Q) — The proportion of consumed food that is converted into production (new biomass) by a functional group. Typically ranges between 0.05 and 0.3 for most groups.

Omnivory Index (OI) — A measure of the diversity of trophic levels from which a consumer feeds. An OI of zero indicates the predator feeds on prey from only one trophic level; higher values indicate feeding across multiple trophic levels.

System Omnivory Index (SOI) — The weighted average of the omnivory indices of all consumer groups in the ecosystem. Higher SOI values (generally > 0.5) are associated with greater ecosystem maturity and more complex feeding interactions.

Lindeman Spine — A simplified linear representation of the food web that aggregates all flows into discrete integer trophic levels, starting from primary producers and detritus. Used to visualize energy transfer efficiencies between successive trophic levels.

Trophic Efficiency (Transfer Efficiency) — The percentage of production at one trophic level that is converted into production at the next higher trophic level. Classically approximated near 10 %, though actual values vary.

Niche Overlap — An index (ranging from 0 to 1) that quantifies the degree of shared resource use between two species or functional groups. A value of 0 indicates no overlap; a value of 1 indicates complete overlap.

Total System Throughput (TST) — The sum of all flows in the ecosystem (consumption, exports, respiration, and flows to detritus). It represents the system's overall size and activity.

Finn's Cycling Index (FCI) — The proportion of total system throughput that is recycled within the ecosystem. Higher values indicate greater internal recycling and are often associated with ecosystem maturity and resilience.

Finn's Mean Path Length (FML) — The average number of trophic steps that energy or material travels through the food web before leaving the system. Longer path lengths generally indicate more complex and mature ecosystems.

Ascendency (AS) — A network index that combines the size (total system throughput) and organization (average mutual information) of the ecosystem. Higher ascendency is typically associated with more developed systems.

System Overhead (SO) — The "reserve" capacity of the ecosystem, representing alternative energy pathways that provide resilience against perturbations. Calculated as System Capacity minus Ascendency.

Redundancy — The portion of system overhead associated with internal flows. It quantifies multiple parallel energy pathways and contributes to ecosystem stability.

Connectance Index (CI) — The ratio of the number of actual feeding links to the maximum possible number of links in the food web. Higher values indicate greater trophic complexity.

Pedigree Index — A quality index (ranging from 0 to 1) that evaluates the reliability of the input data used to construct the model, based on the origin and precision of each parameter.

Primary Production / Respiration (TPP/TR) — The ratio of total primary production to total respiration. A value near 1 is characteristic of mature ecosystems; values much greater than 1 indicate immature or developing systems.

Primary Production / Biomass (TPP/TB) — The ratio of total primary production to total biomass. Lower values are typical of mature ecosystems with high accumulated biomass relative to production.

Biomass / Total System Throughput (TB/TST) — An index of the Efficiency with which energy flow supports standing biomass. Values increase with ecosystem maturity.

Net System Production (NSP) — Total primary production minus total respiration. High values indicate immature systems; values near zero characterize mature ecosystems.

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IMPORTANCE OF ZINC IN VEGETABLE CROP NUTRITION IN INDIA

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Abstract
Zinc (Zn) is an essential micronutrient for healthy growth, productivity, quality, and nutritional value of vegetable crops. In India, zinc deficiency is increasingly important because of intensive cultivation, imbalanced fertilization, declining soil organic matter, and limited micronutrient replenishment. Vegetables such as tomato, cauliflower, cabbage, onion, potato, cucurbits, and legumes can show reduced growth and yield under inadequate Zn supply. Zinc participates in enzyme activity, protein synthesis, photosynthesis, hormone regulation, and reproductive development. Integrated zinc management through soil testing, balanced fertilization, organic amendments, foliar application, and efficient fertilizers can improve Zn availability, crop productivity, and vegetable nutritional quality. The aim of this paper is to examine the importance of zinc (Zn) in vegetable crop nutrition in India, with emphasis on its physiological functions, deficiency symptoms, soil and crop factors affecting Zn availability, effects on growth, yield and produce quality, and practical approaches for improving Zn-use efficiency. The paper also highlights integrated zinc management through soil testing, balanced fertilization, organic amendments, soil and foliar application, and efficient zinc fertilizers to enhance vegetable productivity, nutritional quality, soil health, and sustainable vegetable production.

Keywords: Zinc; micronutrient nutrition; vegetable crops; zinc deficiency; zinc-use efficiency; soil fertility; foliar application; integrated nutrient management; vegetable quality; sustainable agriculture.

Introduction

Modern Indian agriculture has experienced a distinct paradigm shift, moving rapidly from traditional cereal-dominated cropping patterns toward high-intensity horticultural systems. Driven by growing urban demand and higher economic returns, vegetable cultivation plays a vital role in national food and nutritional security. However, this intensive cultivation, characterized by heavy biomass extraction and high-yielding hybrids, has placed immense pressure on soil nutrient reserves. While macro-nutrients (Nitrogen, Phosphorus, and Potassium) receive primary attention, micronutrient deficiencies have silently emerged as severe yield-limiting factors across India's vegetable belts. Among these, Zinc (Zn) deficiency stands out as the most pervasive and economically damaging.

Vegetable crops, specifically high-value Solanaceous types (*tomato, brinjal, chilli*) and Cole crops (*cabbage, cauliflower*), exhibit extreme sensitivity to zinc availability. Zinc acts as a vital spark in plant metabolism, driving enzyme activation, hormonal balance, protein synthesis, and carbohydrate transformation. When zinc levels drop below critical thresholds, metabolic pathways stall, leading to visible physiological disorders, stunted development, delayed maturity, and poor-quality produce. For small and marginal Indian farmers, this translates directly into rejected mandi

consignments and severe economic losses. This paper comprehensively covers the physiological importance of zinc, the underlying geogenic and anthropogenic causes of its depletion in Indian soils, diagnostic criteria, crop-specific deficiency symptoms, and modern integrated management strategies.

Physiological and Biochemical Functions of Zinc

Zinc is a critical micronutrient required continuously across all stages of vegetable development. Although required in trace quantities, its biochemical absence halts vital cellular operations. Its primary physiological contributions include:

Catalytic and Enzymatic Activation: Zinc operates as an essential structural component or co-factor for over 300 plant enzymes. It plays a foundational role in the activity of Carbonic Anhydrase (CA), an enzyme localized within both the cytoplasm and chloroplasts that catalyzes the reversible hydration of carbon dioxide. A decline in CA activity under zinc stress severely limits the supply of CO_2 to the Rubisco enzyme, directly lowering the net photosynthetic rate of the crop. Additionally, zinc activates crucial dehydrogenases, proteinases, and peptidases involved in general respiration and energy metabolism.

Auxin Biosynthesis and Tryptophan Expression: One of the most profound effects of zinc nutrition in vegetables is its direct involvement in the synthesis of Indole-3-Acetic Acid (IAA), the principal endogenous plant auxin responsible for cell division, elongation, and apical dominance. Zinc is an absolute requirement for the biosynthesis of tryptophan, the amino acid precursor to IAA. Under zinc deficiency, tryptophan synthesis is blocked, resulting in a collapse of internal auxin levels. This hormonal failure causes the shortened internodes, miniature leaves, and severe rosetting characteristically seen in zinc-starved field crops.

Ribosomal Stability and Protein Synthesis: Zinc plays a vital role in maintaining the structural integrity of cytoplasmic ribosomes. In its absence, ribosomes undergo rapid disintegration, causing protein synthesis to stall. Zinc also protects cellular components by stabilizing RNA and DNA structures and regulating the expression of zinc-finger transcript factors involved in stress response pathways. Furthermore, zinc is actively involved in maintaining membrane stability by controlling the generation of reactive oxygen species (ROS). It acts as a structural component of Copper-Zinc Superoxide Dismutase (Cu-Zn SOD), a crucial antioxidant enzyme that scavenges cytotoxic free radicals, protecting chloroplast membranes from lipid peroxidation under environmental stress.

Geogenic and Anthropogenic Causes of Zinc Deficiency

Widespread data gathered through the Government of India's Soil Health Card Scheme reveals that approximately 40% to 45% of Indian agricultural soils are deficient in available zinc. This extensive depletion stems from a combination of natural soil formation processes and unscientific management practices:

- **Geogenic Fixation in High pH Profiles:** In high pH soils (>7.5is greater than 7.5 >7.5), common across the Indo-Gangetic plains of Uttar Pradesh and Bihar, as well as the black soil regions of Central India, zinc availability declines steeply. For every unit increase in soil pH above 6.0, zinc solubility decreases thirty-fold due to the formation of insoluble zinc carbonates, zinc hydroxides, and solid-phase calcium zincates. This renders the inherent soil zinc unavailable to plant roots.
- **Exploitative Intensive Agriculture:** Continuous intensive cropping, such as the classic rice-wheat or rice-vegetable rotations, without adequate organic recycling or micronutrient replenishment, has rapidly depleted the labile pool of soil zinc.

- **Phosphorus-Induced Zinc Antagonism:** A major anthropogenic trigger for zinc deficiency is the continuous, unmonitored application of high-analysis phosphatic fertilizers, particularly Di-ammonium Phosphate (DAP). High concentrations of phosphorus ions in the soil solution react directly with zinc to form highly insoluble Zinc Phosphate [$Zn_3(PO_4^2$] precipitates. This chemical locking occurs both in the soil matrix and within the plant root tissue itself, obstructing the translocation of zinc from roots to upper shoots. This phenomenon is widely termed "Phosphorus-Induced Zinc Antagonism".
- **Low Soil Organic Carbon and Sandy Texture:** Coarse-textured sandy soils, typical of parts of Punjab, Haryana, and Rajasthan, possess inherently low Cation Exchange Capacity (CEC) and low organic matter carbon (<0.5%. These factors accelerate the leaching of trace elements, resulting in true geogenic zinc deficiency.

Diagnostic Criteria and Critical Limits

Accurate diagnosis of zinc status relies on quantitative metrics derived from soil and plant tissue analysis rather than visual observation alone.

4.1 Soil Diagnostic Metrics: The national standard for measuring plant-available zinc in Indian laboratories is the DTPA (Diethylenetriaminepentaacetic acid) extraction method developed by Lindsay and Norvell. Under the Soil Health Card guidelines, the critical limits for DTPA-extractable zinc are classified as follows:

Critical limits for DTPA-extractable zinc

- **Critical Threshold (Deficient):** <0.6mg/kg (ppm) - Strong crop response to external zinc application is guaranteed.
- **Marginal Status:** 0.6 to 1.2 mg/kg (ppm) - Hidden hunger may occur; recommended for high-yielding vegetable cultivars.
- **Sufficient Range:** 1.2 to 2.5 mg/kg (ppm) : Adequate for standard crop requirements.
- **Toxicity Threshold:** >10.0 mg/kg (ppm). Highly rare in India, occasionally found near industrial sewage discharge zones.

Plant Tissue Diagnostic Metrics

To monitor nutrient status during the active vegetative growth phase, index tissue sampling (typically the most recent fully expanded leaves) is performed. For most commercial vegetables, leaf tissue zinc concentrations below 20 ppm signal acute deficiency. The optimal range lies between 20 to 50 ppm, whereas heavy feeding cole crops (cabbage and cauliflower) can safely accumulate up to 100–200 ppm without displaying signs of toxicity.

State-Wise Zinc Deficiency Status Across Major Indian Vegetable Belts

The intensity and geographical distribution of zinc deficiency vary according to regional soil conditions and cropping histories. The table below outlines the deficiency distribution across major agricultural states:

State	Dominant Soil Typology	Mean Available Zn Range (ppm)	Estimated Soil Deficiency (%)
Uttar Pradesh	Alluvial (Indo-Gangetic Plain), Alkaline patches	0.32 – 0.75	42% – 48%
Punjab & Haryana	Coarse Sandy Loam, Low Organic Carbon	0.28 – 0.68	38% – 45%

State	Dominant Soil Typology	Mean Available Zn Range (ppm)	Estimated Soil Deficiency (%)
Maharashtra	Deep Black Clayey (Vertisols), High pH	0.35 – 0.80	40% – 50%
Bihar	Calcareous Alluvial, Active Floodplains	0.25 – 0.60	45% – 52%
Karnataka	Red Sandy Loams (Alfisols), Lateritic soils	0.40 – 0.95	35% – 42%
Gujarat	Alluvial Saline-Alkaline, Black Cotton soils	0.30 – 0.85	37% – 44%

Crop-Specific Zinc Deficiency Symptoms

Vegetable crops display distinct, visible physiological reactions when zinc supply is restricted. Early field identification allows for rapid corrective measures before yield damage becomes irreversible. Here is the curated catalogue of visual diagnostic references for zinc deficiency across major Indian vegetable crops.

Zinc Deficiency in Tomatoes (*Solanum lycopersicum*): Tomatoes exhibit high sensitivity to zinc starvation. The earliest symptom appears on young, expanding leaves as pronounced interveinal chlorosis, where the leaf tissue between the main veins turns pale yellow while the veins remain green. As the deficiency intensifies, minor veins also lose colour. Due to the breakdown of auxin pathways, leaf expansion is severely restricted, causing leaflets to become small, narrow, and structurally distorted, with upward curling margins. The internodes shorten dramatically, creating a stunted, bushy growth pattern. Flowering is heavily suppressed, flower drop increases, and any fruit that sets remains small, woody, and ripens unevenly, drastically lowering market value.



Figure 1. Zinc Deficiency in tomato*:* Note the distinctive interveinal chlorosis appearing first on younger expanding leaves, followed by margin distortion, upward curling, and highly restricted leaf expansion (Reference: Yara UK / TNAU Agritech Portal).

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Zinc Deficiency in Chilli and Capsicum (*Capsicum annuum*): Chilli and capsicum varieties react to zinc stress through distinct structural deformations. Leaves become narrow, elongated, and highly asymmetrical, a condition often described as "strap-leaf". The margins display irregular wavy twisting or downward cupping. Older foliage develops bronzed chlorotic patches that eventually turn necrotic. The structural canopy remains restricted, and the plants exhibit severe bud drop. The few pods that develop are small, misshapen, thin-walled, and highly susceptible to sun-scald, making them unmarketable in regional mandis.



Figure 2. Zinc deficiency in Chilli/Capsicum crops, presenting as significantly narrow, elongated, asymmetrical "strap-leaves" with wavy margins, shortened internodes creating stunted plant stature, and severe interveinal mottling (Reference: Plantix Network / Agrio Library).

Zinc Deficiency in Brinjal/Eggplant (*Solanum melongena*): In brinjal cultivation, zinc deficiency triggers a classic physiological abnormality widely known as "Little Leaf Disease of Brinjal". Due to the lack of IAA auxin production, the leaf blades fail to expand, resulting in tiny, leathery, chlorotic leaves. The drastic shortening of stem internodes forces these miniature leaves to cluster together tightly, causing severe rosetting of the foliage. Affected brinjal bushes take on a compacted, flat appearance. The plant's reproductive capacity drops sharply, leading to premature bud abortion, lack of fruit set, and complete loss of commercial yield.



Figure 3. Zinc Deficiency in Brinjal (Egg plant): Severe Zinc deficiency manifestation in Brinjal (Eggplant), demonstrating structural "little leaf syndrome", severe leaf reduction, extreme rosetting due to compressed internodal lengths, and pale yellowing patches across the foliage profiles (Reference: TNAU Agritech / Kerala Agricultural University Portal).

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Cole Crops: Cabbage and Cauliflower (*Brassica oleracea*): Cole crops are heavy nutrient consumers and show clear symptoms of zinc deficiency during their critical head and curd formation stages. Early signs include a general paling and distinct mottling of the younger outer leaves, which develop a dull bronze tint along their margins. Internodes remain compressed, reducing head volume in cabbage and causing small, loose, discoloured curds in cauliflower. Furthermore, the structural synchronization of head formation is broken, leading to uneven crop maturity across the field. In severe cases, internal tissues display hollow stem disorders, rendering the harvest unmarketable.



Figure 4. Zinc deficiency in Cole Crops: Cabbage and Cauliflower (Brassica oleracea). Early signs include a general paling and distinct mottling of the younger outer leaves, which develop a dull bronze tint along their margins.

Zinc deficiency in Cucurbits: Zinc deficiency in cucurbit crops such as cucumbers, squash, and melons is a common micronutrient disorder that impairs vital enzyme functions and growth regulation, which ultimately reduces overall fruit yield. This deficiency primarily shows up on new leaves as interveinal chlorosis, where the tissue between the veins turns yellow or white while the main veins stay green, and it leads to severely stunted stem spaces that cause leaves to become small, bunched, or malformed before they eventually turn brown, dry up, and drop off prematurely. These symptoms are typically triggered by high soil pH levels above 7.0 or excess phosphorus fertilization that restricts zinc uptake, though cold, wet, and compacted soils also slow down root absorption. Growers can quickly resolve the issue during the growing season by applying a foliar spray of Zinc Sulphate directly to the leaves, or they can prevent it long-term by mixing zinc fertilizers into the soil before planting and adding organic compost to maintain a balanced, near-neutral pH.

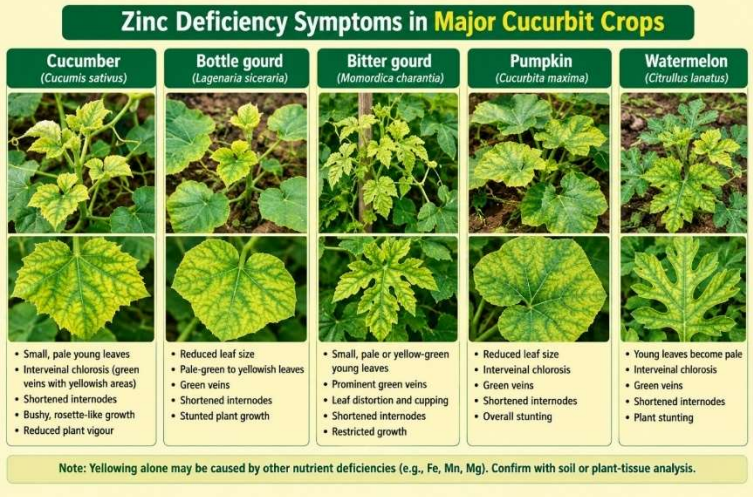


Figure 5. Zinc deficiency in Cucurbits

Zinc deficiency symptoms in Potato: *Zinc deficiency in potatoes drastically* restricts growth during early vegetative development by disrupting hormone production and cell elongation. The most prominent symptom is the "little leaf" or "fern leaf" deformity, where the youngest leaflets fail to expand normally, growing narrow, small, and cupping tightly inward to create a bunched, rosette appearance at the top canopy. Because stem spaces (internodes) remain extremely short, the plant takes on a severely compressed, stunted, and bushy shape.

Visually, new leaves display distinct, patchy interveinal chlorosis, turning pale green or yellow while the main veins stay green. As the deficiency advances, irregular greyish-brown or whitish necrotic spots develop within the yellowed tissue, and leaf margins begin to scorch. Ultimately, this lack of healthy canopy development delays crop maturity, severely reducing final tuber size and total marketable field yield.



Figure 6. Zinc deficiency in Potato

Zinc fertilizer sources as per FCO standard

As per India's Fertilizer Control Order (FCO), zinc fertilizers are regulated, and only specific sources/forms are approved for agricultural use. These are broadly grouped into inorganic salts, chelated forms, and fortified fertilizers.

Primary zinc fertilizer sources

The most common straight **zinc fertilizers** included under FCO are the following:

- Zinc sulphate ($ZnSO_4$)
    - Zinc sulphate heptahydrate (~21% Zn)
    - Zinc sulphate monohydrate (~33% Zn)
    - This is the most widely used and standard FCO zinc fertilizer.
- Zinc oxide (ZnO)
    - Used mainly in suspension/liquid formulations
- Zinc carbonate ($ZnCO_3$) *(limited use)*

Chelated / complex zinc fertilizers (FCO grade)

These are more efficient (especially in high pH soils):

- Zn-EDTA (Chelated zinc, usually 12% Zn)
- Other chelates (less common in India): Zn-HEDTA, Zn-NTA

Zinc in fortified / mixed fertilizers

FCO also permits zinc to be supplied through fortified fertilizers, such as

- Zincated NPK fertilizers
- Zincated DAP (Di-ammonium phosphate)
- Zincated SSP (Single super phosphate)
- Micronutrient mixtures containing zinc

Other recognized zinc forms (less common but technically included)
(Depending on formulation approval and standards)

- Zinc oxysulphate
- Basic zinc sulphate
- Zinc chloride / nitrate (rare in field use)

Modern Corrective Measures and Management Options
To successfully manage zinc deficiency in Indian vegetable systems, a strategic approach combining traditional soil management with modern nutrient delivery technologies is required.

Basal Soil Fertilization: For fields confirmed to have low DTPA-extractable zinc (<0.6 ppm), basal soil application stands as the most reliable long-term solution. The standard agronomic recommendation is the application of 25 kg/hectare of Zinc Sulphate Heptahydrate (21% Zn) or 15 kg/hectare of Zinc Sulphate Monohydrate (33% Zn) during final land preparation. This soil application provides residual benefits that typically last for two to three successive cropping seasons.

Crucial Application Rule: Zinc sulphate must never be mixed directly with phosphatic fertilizers like DAP, NPK complex mixtures, or Single Super Phosphate (SSP) in the fertilization tank or mixing bowl. Doing so triggers immediate chemical precipitation into insoluble zinc phosphate. Zinc fertilizers should be applied separately, either via broad broadcasting before phosphate application or via targeted bands adjacent to the transplanting rows.

Foliar Intervention with Chelated Formulations: When a standing vegetable crop displays visible deficiency symptoms or when high soil pH (>7.5is greater than 7.5 >7.5) immobilizes soil-applied zinc, foliar spraying offers a rapid, highly targeted remedy. Under these conditions, Chelated Zinc (Zinc-EDTA 12%) is the ideal choice. The ethylenediaminetetraacetic acid (EDTA) molecule encapsulates the zinc ion, preventing it from reacting with other elements or being fixed on the leaf surface.

Application Protocol: Dissolve 0.5 to 1.0 gram of Zn-EDTA (12%) per litre of water (100–200 grams/acre in 200 litres of water). Apply using a well-calibrated knapsack sprayer, ensuring uniform coverage of both upper and lower leaf surfaces. For best results, spray during the cooler hours of the day—early morning or late evening—to maximize stomatal absorption and avoid any risk of leaf scorch. Repeat the application 10–14 days later if deficiency symptoms persist.

Advanced Nanotechnology Delivery Systems: A significant technological advance in micronutrient delivery is the development of liquid nano-fertilizers, notably IFFCO Nano Zinc. This formulation contains structured zinc nanoparticles engineered with a high surface-area-to-volume ratio. These ultra-small particles easily penetrate the cuticle and stomatal pores of vegetable leaves, providing high bioavailability within the plant's vascular system.

By bypassing soil fixation completely, IFFCO Nano Zinc achieves high nutrient-use efficiency at very low application rates compared to traditional mineral salts. Foliar application of Nano Zinc quickly

resolves internal zinc deficiencies, promotes metabolic enzyme pathways, enhances resistance to climatic stress, and improves both fruit quality and overall yield. It represents a highly efficient, sustainable choice for modern Indian vegetable growers looking to optimize input costs.

Integrated Nutrient Management (INM): To optimize zinc availability over time, chemical fertilizers should be paired with organic soil amendments. Incorporating 10 to 15 tonnes/hectare of well-decomposed Farmyard Manure (FYM), compost, or vermicompost during initial plowing is highly effective. As organic matter decomposes, it releases natural organic acids and fulvic compounds that act as natural chelating agents. These compounds bind with native soil zinc, preventing its fixation into insoluble mineral complexes and ensuring a steady supply of plant-available zinc throughout the crop cycle.

Conclusion

Zinc nutrition is a foundation of successful, high-yielding vegetable production in India. Given that nearly half of the country's agricultural soils suffer from zinc depletion, continuing with traditional, macro-nutrient-only fertilization programs limits crop performance and reduces farmer profitability. Zinc starvation disrupts critical pathways including enzyme activation, auxin synthesis, and protein stability leading to significant visual defects and structural yield losses in high-value solanaceous and cole crops. By adopting systematic diagnosis via the Soil Health Card scheme, respecting soil chemistry boundaries, and utilizing advanced nutrient options like chelated Zn-EDTA and IFFCO Nano Zinc integrated with organic matter management, Indian vegetable growers can protect their crops, improve produce quality, and secure better returns in competitive agricultural markets.

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EDIBLE COATINGS FOR FISH: A SUSTAINABLE APPROACH TO QUALITY PRESERVATION AND SHELF-LIFE EXTENSION

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Abstract
Fish is one of the most nutritious foods available, but it is also highly perishable because of its high moisture content, endogenous enzymatic activity, microbial growth and susceptibility to lipid oxidation. Maintaining fish quality after harvest therefore requires effective temperature control, hygienic handling and appropriate preservation technologies. Edible coatings have emerged as a promising complementary approach for extending the shelf life of fresh and processed fish. These coatings are thin layers of food-grade materials formed directly on the surface of fish products. Polysaccharides such as chitosan, alginate and carrageenan, proteins including gelatin and collagen, and composite formulations can act as barriers against oxygen and moisture while serving as carriers for antimicrobial and antioxidant compounds. Recent studies have demonstrated the potential of chitosan, gelatin, plant extracts and essential oils to retard microbial growth, lipid oxidation, moisture loss and other quality changes during storage. The development of active and intelligent edible coatings further expands their potential applications in sustainable seafood preservation. However, formulation, sensory acceptability, water-vapour barrier properties, processing conditions, food safety and industrial scalability remain important challenges. This article discusses the principles, materials, mechanisms, applications and future prospects of edible coatings for fish preservation.

Keywords: Edible coating, fish preservation, chitosan, gelatin, alginate, antioxidants, essential oils, shelf life, sustainable packaging

Introduction

Fish is an important source of high-quality protein, omega-3 polyunsaturated fatty acids, vitamins and minerals. Despite its nutritional value, fish is among the most perishable foods because of its high moisture content, relatively high-water activity, endogenous enzymes and susceptibility to microbial spoilage and lipid oxidation. Once fish is harvested, a series of biochemical and microbiological changes begin to affect its quality. Enzymatic reactions can alter texture, microorganisms can generate undesirable metabolites and volatile compounds, and oxidation of unsaturated lipids can lead to rancid flavours and off-odours. Cold storage and icing remain essential methods for maintaining fish quality. Other preservation approaches include freezing, drying, salting, smoking, modified-atmosphere packaging and thermal processing. However, increasing consumer demand for minimally processed, natural and sustainable foods has encouraged researchers to explore additional preservation technologies.

One promising approach is the use of edible coatings.

A recent comprehensive review described edible coatings as an emerging technology for fish preservation, emphasizing their potential to control physical, chemical, microbiological and sensory deterioration during storage (Kurek et al., 2024).

What Are Edible Coatings?

An edible coating is a thin layer of food-grade material applied directly to the surface of a food product. Unlike conventional packaging, the coating becomes part of the food system and can potentially be consumed along with the product.

Coatings can be produced from different classes of materials.

Polysaccharides

Examples include:

- Chitosan
- Alginate
- Carrageenan
- Pectin
- Starch
- Natural gums

Proteins

Examples include:

- Gelatin
- Collagen
- Whey proteins
- Soy proteins
- Zein

Lipids

Examples include:

- Waxes
- Fatty acids
- Lipid-based compounds

Each material has specific advantages and limitations. Therefore, researchers increasingly combine two or more components to create composite coatings with improved properties.

Why Does Fish Need Protective Coating?

Fish deterioration occurs through multiple mechanisms simultaneously. A suitable coating can help slow several of these processes.

A protective coating can:

- Reduce oxygen transfer
- Reduce moisture loss
- Limit surface dehydration
- Slow lipid oxidation
- Reduce microbial growth
- Protect colour
- Improve texture retention
- Carry antioxidants and antimicrobial compounds

The exact coating requirements depend on the species and storage conditions.

For example, fatty fish require considerable protection against oxidation because of their high content of unsaturated lipids. Frozen fish may require greater protection against dehydration and freezer burn.

Kurek *et al*., (2024) emphasized that coating composition should be considered in relation to the fish species, storage temperature and desired preservation function.

Chitosan: A Promising Biopolymer

Among the different materials investigated for seafood preservation, **chitosan** has received considerable attention.

Chitosan is obtained by deacetylation of chitin, a structural polysaccharide found abundantly in the shells of crustaceans such as shrimp, crab and lobster.

This is particularly interesting for the seafood sector because a processing by-product can serve as a source of a value-added biomaterial.

Chitosan possesses film-forming ability and natural antimicrobial properties. Chitosan-based coatings can also provide useful oxygen and gas-barrier properties.

A 2024 review reported that chitosan-based films and coatings can help protect foods against microbial growth and oxidative deterioration while providing a biodegradable alternative to conventional petroleum-derived packaging materials.

However, chitosan is hydrophilic and therefore has limitations as a moisture barrier. This has encouraged the development of composite coatings incorporating proteins, lipids or other polymers.

Gelatin and Collagen-Based Coatings

Gelatin and collagen are attractive materials for seafood applications because they are protein-based and can be obtained from animal-derived processing materials.

Fish skin, scales and bones can serve as sources of collagen and gelatin, providing opportunities for value addition.

Combining gelatin with chitosan can improve the functional characteristics of coatings. Recent research has investigated chitosan-gelatin systems containing plant extracts for preservation of fresh tuna products.

Such formulations are being explored for their ability to combine film-forming capacity with antimicrobial and antioxidant functions.

Therefore, seafood processing by-products can potentially become raw materials for developing the next generation of edible preservation systems.

Active Edible Coatings

Traditional edible coatings mainly act as physical barriers. The newer generation of coatings can be **active**, meaning that functional compounds are incorporated into the coating.

Potential active ingredients include:

- Essential oils
- Plant extracts
- Phenolic compounds
- Natural antioxidants
- Organic acids
- Antimicrobial compounds

- Bioactive peptides

Essential oils from plants such as clove, oregano, thyme, cinnamon and other aromatic plants have been investigated because of their antimicrobial and antioxidant properties.

However, concentration must be carefully controlled. Excessive amounts may produce strong aromas or flavours that negatively affect consumer acceptability.

How Do Edible Coatings Preserve Fish?

1. Control of oxygen

Oxygen can accelerate lipid oxidation. A coating with good oxygen-barrier properties can reduce oxygen transfer to the fish surface and thereby slow oxidative deterioration.

2. Control of moisture

Fish can lose water during storage, resulting in dehydration, weight loss and changes in appearance and texture. A suitable coating can reduce moisture migration.

3. Antimicrobial activity

Certain coating materials, particularly chitosan and coatings containing selected essential oils or plant extracts, can inhibit the growth of spoilage microorganisms.

4. Antioxidant activity

Natural antioxidant compounds can slow lipid oxidation and reduce the formation of undesirable oxidation products.

5. Protection of sensory quality

By slowing microbial and chemical deterioration, coatings can help maintain desirable colour, texture, flavour and odour.

Edible Coatings for Chilled Fish

Chilled fish is particularly susceptible to microbial deterioration. Therefore, coatings designed for refrigerated storage generally focus on antimicrobial activity combined with oxygen and moisture control.

The recent literature shows that chitosan, alginate, gelatin and composite coatings have been investigated in different fish species.

The effectiveness depends on:

- Coating concentration
- Type of polymer
- Active compound
- Fish species
- Initial microbial load
- Storage temperature
- Coating thickness
- Application method

Thus, there is no single coating formulation that is universally suitable for every fish product.

Edible Coatings for Frozen Fish

Freezing slows microbial and enzymatic activity but does not completely eliminate quality deterioration.

During frozen storage, moisture migration can lead to dehydration and freezer burn, while lipid oxidation may continue at a slower rate.

Edible coatings can provide an additional protective barrier. Recent studies have investigated chitosan, alginate, gelatin and composite formulations for frozen fish and seafood products.

Kurek et al. (2024) reported that coatings can help reduce moisture loss, lipid oxidation and other quality changes during frozen storage. Seaweed-derived materials have also been investigated for their potential protective effects.

This creates an interesting connection between marine biomass and sustainable seafood preservation**.**

Edible Coatings and Seaweed-Based Materials

Seaweeds contain polysaccharides such as alginate, carrageenan and agar, which possess film-forming properties.

These materials are particularly attractive because they originate from renewable marine resources.

Seaweed-derived coatings can potentially be combined with antioxidants, plant extracts or other biopolymers to develop multifunctional preservation systems.

The future therefore lies not simply in replacing plastic with one natural material, but in designing high-performance biodegradable systems using combinations of renewable biomaterials**.**

Smart and Intelligent Coatings

An emerging development is the integration of edible coatings with smart packaging.

Freshness indicators can respond to changes in pH, volatile compounds or other indicators associated with fish spoilage. Such systems can provide consumers and processors with visual information regarding product quality.

Combining

Edible coating + active compound + freshness indicator + appropriate packaging could create multifunctional seafood packaging systems.

This approach could improve not only preservation but also quality monitoring and reduction of food waste.

Recent Evidence

A 2024 review of edible coatings for fish highlighted the importance of matching coating characteristics with storage conditions and fish requirements.

More recent systematic evidence published in 2026 found that chitosan coatings containing essential oils generally extended the refrigerated shelf life of fish and fish products by approximately 2–9 days in the studies reviewed, corresponding to approximately 30–150% improvement compared with untreated controls under the conditions examined (2026 systematic review).

These findings are promising, but laboratory results should not automatically be transferred to commercial processing. Industrial trials are necessary to determine the actual economic and technological feasibility of individual formulations.

Challenges in Commercial Application

Despite their potential, several challenges must be addressed before widespread commercial adoption.

Sensory acceptance

Essential oils and plant extracts can impart strong flavours or aromas. A coating that effectively controls microorganisms may still fail commercially if consumers dislike its sensory characteristics.

Moisture barrier

Many polysaccharides are hydrophilic and therefore do not provide excellent water-vapour resistance.

Uniform application

Industrial processors need coatings to be applied uniformly over complex fish surfaces.

Cost

High-purity bioactive compounds and advanced encapsulation technologies can increase production costs.

Regulatory requirements

All ingredients must be permitted for their intended food use, and safety evaluation is necessary for active compounds and novel formulations.

Scale-up

Many studies are performed under laboratory conditions. Commercial processing involves much larger volumes, faster processing lines and variable raw materials.

Future Prospects

The future development of edible coatings for fish is likely to focus on multifunctional and sustainable systems.

Promising directions include:

- Chitosan-gelatin composite coatings
- Fish collagen and gelatin coatings
- Seaweed-polysaccharide coatings
- Nano- and microencapsulation of active compounds
- Essential-oil-loaded coatings
- Plant-extract-enriched coatings
- Active and intelligent packaging
- Combination with modified-atmosphere packaging
- Utilization of seafood processing by-products
- Species-specific coating formulations

An especially promising concept is the conversion of seafood processing residues into coating ingredients. Fish skin, scales and bones can provide collagen and gelatin, while crustacean shells can provide chitin and chitosan.

Thus, edible coatings can contribute not only to food preservation but also to circular bioeconomy development**.**

Conclusion

Edible coatings represent a promising technology for improving the storage stability and quality of fish and seafood products. Polysaccharides such as chitosan and alginate and proteins such as gelatin and collagen can provide protective barriers against oxygen and moisture while also serving as carriers for natural antimicrobial and antioxidant compounds.The technology is particularly attractive because it can combine food preservation, reduction of food waste, renewable materials and circular utilization of seafood processing by-products**.**Nevertheless, edible coatings should be regarded as a complementary preservation technology rather than a replacement for hygienic handling and proper temperature control. Future research should focus on sensory acceptability, regulatory safety, industrial scale-up, cost reduction and species-specific formulations.The integration of edible coatings with active ingredients, intelligent packaging and cold-chain technologies could contribute to the development of safer, longer-lasting and more sustainable seafood products.

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ENCAPSULATION TECHNOLOGIES FOR BIOACTIVE COMPOUNDS IN FOOD: A REVIEW OF PROBIOTICS, POLYPHENOLS, AND OMEGA-3 FATTY ACIDS

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Abstract

Probiotics polyphenols and omega-3 fatty acids are among the most researched bioactive compounds in functional food development thanks to their proven roles in gut health antioxidant defense and cardiovascular protection. Yet turning these benefits into real food products is far from simple. These compounds tend to break down when exposed to heat light oxygen or acidic conditions. Many also suffer from poor solubility limited absorption in the gut and sensory issues like bitterness or fishy odors that consumers find unappealing. Encapsulation technology has become a practical solution to these problems. By enclosing bioactive compounds within a protective coating or matrix food scientists can shield them from degradation improve their stability during storage and processing and control how and where they are released in the body. This review brings together current research on the major encapsulation techniques used for these three bioactive groups. It covers widely used methods such as spray drying freeze drying coacervation emulsification and liposome formation along with newer approaches like electrospinning and nanoencapsulation. Each technique is examined for its suitability to specific compounds since probiotics polyphenols and omega-3s each present their own unique protection and delivery challenges. The review also looks at how these encapsulated systems are evaluated in terms of particle characteristics stability and bioavailability and how well they perform once incorporated into actual food products. Despite considerable progress several challenges remain unresolved. High production costs difficulty scaling up advanced techniques and unclear regulatory guidelines for nanoscale ingredients continue to slow commercial adoption. Consumer skepticism toward novel or engineered ingredients adds another layer of complexity. Moving forward the field is likely to benefit from more sustainable encapsulation materials smarter formulation strategies guided by computational tools and a stronger focus on making these technologies both scalable and consumer friendly.

Keywords: Encapsulation, Bioactive compounds, Probiotics, Polyphenols, Omega-3 fatty acids, Controlled release, Functional foods, Bioavailability

Introduction

Probiotics polyphenols and omega-3 fatty acids are central to modern functional food development due to their established links with gut health antioxidant activity and cardiovascular protection. Probiotics are defined as live microorganisms that confer a health benefit when consumed in adequate amounts (Sbehat *et al.,* 2022). Fermented dairy products remain a common vehicle for delivering these compounds to consumers (Gruškienė *et al.,* 2021).Direct incorporation of these compounds into food systems is difficult. Heat light oxygen and pH changes cause rapid degradation during processing and storage (Nedović *et al.,* 2021). Many bioactives also show poor solubility and

low bioavailability. Sensory issues such as bitterness from polyphenols and fishy odors from omega-3s further limit consumer acceptance. Probiotics face the added challenge of surviving gastric transit where a large share of unprotected cells fail to remain viable.

Encapsulation addresses these problems by enclosing bioactive compounds within a protective matrix. This barrier reduces degradation masks poor sensory attributes and allows controlled release at the desired site within the digestive tract. For probiotics encapsulation has been shown to improve survival through simulated gastric conditions.

This review examines encapsulation technologies used for probiotics polyphenols and omega-3 fatty acids within a single comparative framework. It covers established methods such as spray drying freeze drying coacervation emulsification and liposomal entrapment along with emerging techniques such as electrospinning and nanoencapsulation. The review also outlines current limitations related to scalability regulation and consumer acceptance and points toward future research directions.

Fundamentals of Encapsulation

Encapsulation is the process of enclosing a bioactive compound within a wall material or carrier system to form a distinct core-shell structure. The core holds the active ingredient while the shell acts as a physical barrier against the surrounding environment (Nedović *et al.,* 2021). Depending on the technique and material used the compound may be trapped within a continuous matrix rather than a defined shell giving rise to matrix-type systems alongside true core-shell capsules.

Encapsulation systems are broadly classified by particle size. Microencapsulation produces particles typically ranging from one micrometer to a few hundred micrometers and is widely used for probiotics and polyphenols in food matrices (Sbehat *et al.,* 2022). Nanoencapsulation produces particles below one micrometer and is increasingly applied to omega-3 fatty acids and polyphenols to improve solubility and absorption. Nanoscale systems generally offer higher surface area and improved bioavailability but raise additional concerns around cost and regulatory approval.

An effective wall material must be biocompatible and safe for consumption. It should form a strong barrier against oxygen moisture and light to protect the core compound from degradation. The material should also allow control over release behavior so the active compound is released at the intended time or site rather than immediately upon consumption. Additional desirable properties include good film-forming ability compatibility with the food matrix and minimal impact on taste or texture.

Proteins such as whey protein casein and gelatin are commonly used due to their good emulsifying and film-forming properties. Polysaccharides including alginate chitosan maltodextrin and gum arabic are widely applied for their availability low cost and compatibility with food-grade processing (Gruškienė *et al.,* 2021). Lipid-based materials such as waxes and solid fats are often used in probiotic encapsulation to enhance gastric resistance. Many systems combine two or more of these materials to balance protection efficiency release control and cost.

Encapsulation Techniques

1. Spray drying

Spray drying converts a liquid feed containing the bioactive core and wall material into a dry powder through rapid evaporation using hot air. It is one of the most economical and industrially scalable

encapsulation methods and has been widely applied to protect polyphenols from oxidative and thermal degradation (Fang and Bhandari 2010). The technique works well for polyphenols since short exposure to heat limits degradation while producing stable powders with good encapsulation efficiency (Sun-Waterhouse *et al.,* 2012). Its use for probiotics is more limited because the high inlet temperatures required for drying can reduce cell viability though optimized wall materials and lower temperatures have improved survival rates in several studies (Behboudi-Jobbehdar *et al.,* 2013).

2. Freeze drying

Freeze drying or lyophilization removes water through sublimation under low temperature and vacuum conditions. This makes it the preferred method for heat-sensitive probiotics since it avoids the thermal stress associated with spray drying and generally yields higher cell viability (Sbehat *et al.,* 2022). The main drawbacks are long processing time high energy consumption and high production cost which limit its use at industrial scale compared to spray drying.

3. Coacervation

Coacervation involves the separation of wall material from solution around a core substance either through a single polymer system or through interaction between two oppositely charged polymers in complex coacervation. The technique is widely applied to probiotics and oils since it forms a dense protective shell without exposing the core to heat (Nedović *et al.,* 2021). Complex coacervation is valued for its high encapsulation efficiency though scale-up and cost remain practical concerns.

4. Emulsification-based methods

Emulsification techniques disperse the core compound as droplets within a continuous phase stabilized by an emulsifier. Single emulsions and double emulsions such as water in oil in water are commonly used to protect omega-3 fatty acids from oxidation and to improve sensory acceptability of fish oil enriched products (Tamjidi *et al.,* 2012). Pickering emulsions which use solid particles instead of conventional surfactants to stabilize the droplet interface have gained attention for improved oxidative stability and cleaner label formulation.

5. Liposomes and nanoliposomes

Liposomes are spherical vesicles formed from phospholipid bilayers that can encapsulate both hydrophilic and lipophilic compounds within the same structure making them suitable for polyphenols and omega-3 fatty acids alike (Karadag *et al.,* 2013). Nanoliposomes offer improved bioavailability and cellular uptake due to their small particle size though stability during storage and sensitivity to processing conditions remain ongoing challenges.

6. Extrusion and gelation

Extrusion involves dripping a polymer and core mixture usually sodium alginate through a nozzle into a hardening solution to form gel beads. This method is commonly used for probiotics due to its simplicity mild processing conditions and ability to produce beads with strong gastric resistance (Gruškienė *et al.,* 2021). Its main limitation is the relatively large particle size produced which can affect texture when incorporated into certain food products.

7. Electrospinning and electrospraying

Electrospinning and electrospraying use an electric field to draw a polymer solution into fine fibers or droplets that solidify into micro or nanoscale carriers. These emerging techniques operate at room temperature making them suitable for heat-sensitive compounds including probiotics and

polyphenols. Current limitations include low production yield and the need for further work on scale-up and solvent selection.

8. Nanoencapsulation approaches

Nanoemulsions solid lipid nanoparticles and polymeric nanoparticles represent the main nanoencapsulation systems applied across all three bioactive classes (Hao *et al.,* 2012). These systems improve solubility bioavailability and controlled release due to their small particle size and high surface area. Their application in food systems remains constrained by higher production cost and unresolved regulatory questions around nanoscale ingredients in food.

Table 1. Comparison of encapsulation techniques

Technique	Best suited compound	Typical encapsulation efficiency	Key limitation
Spray drying	Polyphenols moderate for probiotics	70 to 90 percent	Heat sensitivity of probiotic cells
Freeze drying	Probiotics	80 to 95 percent	High cost and long processing time
Emulsification	Omega-3 fatty acids	60 to 85 percent	Physical instability over storage
Liposomes and nanoliposomes	Polyphenols and omega-3s	60 to 90 percent	Storage stability
Extrusion and gelation	Probiotics	80 to 95 percent	Large particle size
Electrospinning and electrospraying	Probiotics and polyphenols	70 to 90 percent	Low production yield
Nanoencapsulation	Probiotics polyphenols and omega-3s	65 to 90 percent	Cost and regulatory uncertainty

Omega-3 fatty acids are particularly prone to oxidative rancidity due to their high degree of unsaturation which leads to the formation of off-flavors and odors during storage. Encapsulation systems for omega-3s are designed primarily to create an oxygen barrier around the lipid core while also reducing the fishy odor that limits consumer acceptance in fortified products such as yogurt and bread (Tamjidi *et al.,* 2012). Emulsion-based and liposomal systems remain the most common approaches for this compound class due to their compatibility with lipid cores.

Release Mechanisms and Controlled Delivery

1. Triggered release

Controlled release systems are designed to release the encapsulated bioactive compound in response to specific environmental triggers rather than immediately upon consumption. pH-triggered release is common for probiotic and polyphenol delivery systems since wall materials such as alginate remain intact under acidic gastric conditions but dissolve in the higher pH environment of the intestine allowing targeted release at the desired site (Gruškienė *et al.,* 2021). Enzymatic triggers rely on digestive enzymes to break down the wall material while temperature-based systems use lipid or polymer carriers that melt or soften at body temperature to release the core compound.

2. Targeted delivery to the gut and colon

Targeted delivery aims to protect bioactive compounds through the upper gastrointestinal tract and release them specifically in the small intestine or colon where absorption or microbial activity is most beneficial. This is particularly important for probiotics since delayed release in the intestinal region improves the likelihood of successful colonization and for polyphenols where colonic release supports interaction with gut microbiota and local antioxidant activity (Sbehat *et al.,* 2022). Multilayer coatings and pH-sensitive polymers are frequently used to achieve this site-specific delivery.

3. Release kinetics models

Release behavior from encapsulated systems is often described using mathematical models that characterize how the core compound diffuses out of the wall material over time. Commonly applied models include first order kinetics the Higuchi model and the Korsmeyer-Peppas model each describing different release mechanisms such as diffusion erosion or swelling of the carrier matrix. These models help researchers predict and compare release profiles across different encapsulation systems and are widely borrowed from pharmaceutical drug delivery literature and applied to food-grade carriers (Nedović *et al.,* 2021).

Characterization Methods

1. Particle size and morphology

Particle size distribution and surface morphology are among the first properties assessed after encapsulation since they influence stability release behavior and sensory integration into food matrices. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are commonly used to visualize capsule shape surface texture and structural integrity while dynamic light scattering (DLS) is used to measure particle size distribution particularly for nanoscale systems (Karadag *et al.,* 2013).

2. Encapsulation efficiency and loading capacity

Encapsulation efficiency reflects the proportion of the bioactive compound successfully retained within the wall material after processing while loading capacity indicates the maximum amount of core material a given carrier system can hold. These values are typically determined through spectrophotometric or chromatographic methods after extracting the core compound from the capsule and are essential for comparing performance across different wall materials and techniques (Fang and Bhandari 2010).

3. Stability testing

Stability testing evaluates how well the encapsulated compound withstands storage conditions such as temperature humidity and light exposure over time. For probiotics this includes monitoring viable cell counts throughout shelf life while for polyphenols and omega-3 fatty acids stability testing often tracks antioxidant activity and oxidation markers respectively (Sbehat *et al.,* 2022). Thermal stability is also assessed through techniques such as differential scanning calorimetry to determine how processing temperatures affect the wall material and core compound.

4. In vitro and in vivo bioavailability assessment

Simulated gastrointestinal digestion models are widely used to evaluate how encapsulated compounds behave under conditions mimicking the stomach and intestine including pH changes and enzymatic activity. These in vitro models provide an initial indication of protective performance

and release behavior before compounds are tested in vivo through animal or human studies which offer more direct evidence of absorption and physiological effect (Nedović *et al.,* 2021). Cell culture models such as Caco-2 monolayers are also commonly used to estimate intestinal absorption of encapsulated bioactives.

Applications in Food Systems

1. Case examples in food matrices

Encapsulated bioactive compounds have been incorporated into a range of food products to improve functionality while maintaining product quality. Dairy products such as yogurt and cheese are among the most common vehicles for encapsulated probiotics and polyphenols since their matrix supports microbial survival and masks sensory defects associated with unprotected bioactives (El-Messery *et al.,* 2019). Encapsulated fish oil has been successfully incorporated into bakery products and yogurt to fortify omega-3 content while reducing the fishy odor and taste that typically limits consumer acceptance of fortified products (Tamjidi *et al.,* 2012). Beverages represent another growing application area particularly for encapsulated polyphenols where stability during liquid storage is otherwise difficult to achieve.

2. Sensory and textural impact

The addition of encapsulated ingredients can influence the texture appearance and mouthfeel of the final food product depending on capsule size and wall material used. Larger capsules produced through extrusion may introduce a gritty texture in smooth food matrices while smaller particles produced through spray drying or nanoencapsulation tend to integrate more seamlessly (Sun-Waterhouse *et al.,* 2012). Sensory evaluation studies are therefore an essential part of product development to confirm that the functional benefit of encapsulation does not come at the cost of consumer acceptability.

3. Regulatory and labeling considerations

The use of encapsulated ingredients particularly at the nanoscale raises additional regulatory questions that vary across regions. Some regulatory bodies require specific labeling or safety assessment for nanoscale food ingredients due to uncertainty around their behavior in the body compared to conventional micro-scale systems (Hao *et al.,* 2012). Clear labeling also matters for consumer transparency since encapsulated ingredients are sometimes perceived as artificial or overly processed which can affect purchasing decisions despite the functional benefits they provide.

Challenges and Limitations

1. Cost and scalability

Advanced techniques such as electrospinning and nanoencapsulation face significant cost and scale-up barriers compared to established methods like spray drying (Hao *et al.,* 2012). Freeze drying and coacervation are similarly limited by long processing times and specialized equipment needs.

2. Regulatory ambiguity

Regulatory frameworks for encapsulated ingredients especially at the nanoscale remain inconsistent across regions. Unclear safety and labeling requirements for nanoscale food ingredients create uncertainty for manufacturers and slow commercial adoption (Hao *et al.,* 2012).

3.Consumer acceptance

Consumers often associate encapsulated or nanoscale ingredients with artificial processing which conflicts with demand for clean label products. This perception gap can limit market adoption even when a system performs well technically (Sun-Waterhouse *et al.,* 2012).

3. Stability and release trade-offs

A wall material built for strong protection may also resist breakdown in the gut limiting bioavailability while one optimized for easy release may offer weaker protection during storage (Nedović *et al.,* 2021). Balancing both requirements remains an ongoing research challenge.

Future Perspectives

1. Sustainable encapsulation materials

Growing consumer demand for clean label products is driving interest in plant-based and biodegradable wall materials as alternatives to synthetic polymers. Agro-industrial by-products such as fruit peels and seed extracts are being explored as low-cost sustainable carriers that also support waste valorization within the food industry (Nedović *et al.,* 2021).

2. AI and machine learning in formulation design

Computational tools are increasingly used to predict optimal wall material combinations processing parameters and release behavior before physical testing. This approach can reduce development time and material waste while improving the precision of encapsulation efficiency and release control (Hao *et al.,* 2012).

3. Personalized nutrition applications

Encapsulation technology is well positioned to support personalized nutrition by enabling tailored release profiles and targeted delivery based on individual digestive conditions or health needs. This is particularly relevant for probiotic strains and bioactive dosing adjusted to specific consumer groups.

4. Scale-up from laboratory to industry

Bridging the gap between laboratory-scale success and industrial production remains a key priority for future research. Continued work on cost reduction process optimization and regulatory clarity will determine how quickly promising techniques such as nanoencapsulation and electrospinning move into commercial food products.

Conclusion

Encapsulation technology offers an effective route for protecting probiotics polyphenols and omega-3 fatty acids from the instability solubility and sensory challenges that limit their direct use in food products. Technique selection depends strongly on the physicochemical nature of each compound with freeze drying and extrusion favored for heat-sensitive probiotics spray drying and liposomal systems well suited to polyphenols and emulsion-based and nanoencapsulation approaches most effective for omega-3 fatty acids. Despite considerable progress challenges around cost scalability regulatory clarity and consumer acceptance continue to limit widespread commercial adoption particularly for advanced nanoscale systems. Closing these gaps will require closer collaboration between food scientists engineers and regulatory bodies alongside continued research into sustainable materials and computationally guided formulation design. As the demand for functional foods continues to grow encapsulation technology is likely to play an increasingly central role in translating the health benefits of bioactive compounds into commercially viable and consumer-accepted products.

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FINANCIAL INCLUSION IN AGRICULTURE SECTOR OF INDIA: AN OVERVIEW

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Abstract
Ensuring that farmers have adequate access to financial resources is a key component for successful rural development strategies. Without sufficient credit support, growth of agriculture cannot be accelerated particularly looking into the status of capital-starved farmers at large. Therefore, farm credit plays a game changer's role in redirecting the agricultural activities according to the needs and priorities of deprived farmers. Agricultural credit becomes a strong force to enhance the production level, productivity and income of the farmers, which ultimately play an important role to alleviate rural poverty. Failure of timely availability of farm credit during peak season derails the farming activities.

Keywords: Agricultural credit, Financial institutes, Access, Nationalization.

Introduction

Agriculture in India is more than an occupation. It is indeed a way of life for majority of Indian population and is at core of socio-economic development of the country. Agriculture sector plays a key role in Indian economy. Even though the contribution of agriculture in overall GDP of the country has declined from 44.5 per cent in 1970-71 to around 20.19 per cent in 2020-21 and 18.8 per cent during 2021-22, agriculture continues to be the principal source of livelihood for around 62 per cent of the country's population (NSO, 2022).

Capital-intensive nature of modern agricultural technology and inadequate savings of the farmers have encouraged the common farmers to go for external finances from different sources, both institutional and non-institutional sources. Credit plays the role of an accelerator in the agricultural development provided it is adequate in quantity, cheap and development oriented. But, Indian agriculture has always remained dominated by small and marginal holders who are often constrained by capital of their own or lack of access to institutional credit in their endeavor to transit from subsistence to commercial production systems. Agricultural credit is very important for sustainable agricultural development to be achieved in any country of the world. Rural credit has proven to be a powerful instrument against poverty reduction and development in rural areas. Farmers were particularly in need of credit because of the seasonal pattern of their activities and the presence of different types of uncertainty in agriculture.

In Indian context the evolution of institutional credit to agriculture could be broadly classified into four distinct phases - 1904-1969 (predominance of co-operatives and setting up of RBI), 1969-1975 [nationalization of commercial banks], 1975- 1990 (setting up of RRB and NABARD) and from 1991 onwards (financial sector reforms). The genesis of institutional involvement in the sphere of agricultural credit could be traced back to the enactment of the Cooperative Societies Act in 1904.

The establishment of the RBI in 1935 reinforced the process of institutional development for agricultural credit.

The major milestones in improving the rural credit include acceptance of Rural Credit Survey Committee Report (1954), nationalization of major commercial banks (1969 and 1980), establishment of Regional Rural Banks (RRBs) (1975), establishment of National Bank for Agriculture and Rural Development (NABARD) (1982), the financial sector reforms (1991 onwards), Special Agricultural Credit Plan (1994-95), launching of Kisan Credit Cards (KCCs) (1998-99), Doubling Agricultural Credit within three years (2004), Agricultural Debt Waiver and Debt Relief Scheme (2008), and the Jan Dhan Yojana (2014) (Kumar *et al*., 2010). Simultaneously, several other measures like establishment of Lead Bank Scheme, direct lending for the priority sectors, banking sector's linkage with the government-sponsored programmes targeted at the poor, Differential Rate of Interest Scheme (DRIS), the Service Area Approach, the SHG-Bank linkage programmes, Special Agricultural Credit Plans, and Rural Infrastructure Development Fund (RIDF) schemes were introduced to enhance the flow of credit to the rural sector. These initiatives gave a positive impact on the flow of rural credit. Introduction of the Kishan Credit Card in 1998-99 was considered as most effective credit system. However, the inadequacy of rural credit especially to agriculture continues to remain a big challenge. The persistence of money lenders in the rural credit market is also often fiercely debated in the policy discourses in India.

From the Table 1, it was observed that the share for the agriculture and allied sector in central budget stands at Rs1,23,960.75 Crores (3.14 per cent) against the total budget of Rs 39,45,000 Crores during the fiscal year 2022-23. The per capita availability during the period was Rs 31,552.73. The compound annual growth rate (CAGR) for the total budget and for agriculture and allied sector over the years were found to be 12.01 per cent and 19.79 per cent, respectively. This clearly indicates that there exists a positive growth trends in the total budget and share of agriculture and allied sector over the years.

Table.1: **Budget allocation of agriculture and allied sector of India from 2000-01 to 2022-23.**

Years	**Total Budget** (Rs in Crores)	**% Increase over previous Year**	**Per capita Availability** (Rs/Person)	**Share of Agriculture and Allied Sector** (Rs in Crores)	**% Share in Total Budget**
2000-01	335523	-	2683.57	3623	1.08
2001-02	364436	8.62	2914.82	3351	0.92
2002-03	414162	13.64	3312.53	3219	0.78
2003-04	471368	13.81	3770.08	3671	0.78
2004-05	497682	5.58	3980.54	4799	0.96
2005-06	506123	1.70	4048.05	5907	1.17
2006-07	583387	15.27	4666.02	7385	1.27
2007-08	712671	22.16	5700.05	8544	1.20
2008-09	883956	24.03	7070.02	9969	1.13
2009-10	1024487	15.90	8194.01	10123	0.99
2010-11	1197328	16.87	9576.42	14362	1.20

Years	Total Budget (Rs in Crores)	% Increase over previous Year	Per capita Availability (Rs/Person)	Share of Agriculture and Allied Sector (Rs in Crores)	% Share in Total Budget
2011-12	1304365	8.94	10432.52	14855	1.14
2012-13	1410372	8.13	11280.38	15971	1.13
2013-14	1559447	10.57	12472.70	17577	1.13
2014-15	1663673	6.68	13306.32	10199	0.61
2015-16	1790783	7.64	14322.96	10942	0.61
2016-17	1975194	10.30	15797.91	53806	2.72
2017-18	2141973	8.44	17131.84	56589	2.64
2018-19	2315113	8.08	18516.64	86602	3.74
2019-20	2686330	16.03	21485.69	120835	4.50
2020-21	3450305	28.44	27596.08	145355	4.21
2021-22	3483236	0.95	27859.47	118257.69	3.40
2022-23	3945000	13.26	31552.73	123960.75	3.14
CAGR	**12.01**	-	-	**19.79**	-

Source: Ministry of statistics and programme implementation, GoI (2021-22).

The target, per capita availability and achievement of agricultural credit from various institutional sources across the country for the period 2004-05 to 2021-22 were presented on Table 2 and it is observed that the compound annual growth rate during the period shows positive trends over the years. During 2020-21, the achievement was Rs 15,75,398 Crores (105 per cent) against the target of Rs 15,00,000 Crores set by the various financial institutes across the country.

Table.4.2: **Target and achievement of agricultural credit from institutional sources in India**

(Rs in Crores)

Year	Target	Per Capita Availability (Rs)	Achievement	% of Achievement
2004-05	105000	8838.38	125309	119
2005-06	141000	11868.69	180486	128
2006-07	175000	14730.64	229400	131
2007-08	225000	18939.39	254657	113
2008-09	280000	23569.02	301908	108
2009-10	325000	27356.90	384514	118
2010-11	375000	31565.66	468219	125
2011-12	475000	39983.16	511029	108
2012-13	575000	48400.67	607376	106
2013-14	700000	58922.56	730123	104

Year	Target	Per Capita Availability (Rs)	Achievement	% of Achievement
2014-15	800000	67340.07	845328	106
2015-16	850000	71548.82	915510	108
2016-17	900000	75757.58	1065756	118
2017-18	1000000	84175.08	1162617	116
2018-19	1100000	92592.59	1256830	114
2019-20	1350000	113636.36	1392729	103
2020-21	1500000	126262.63	1575398	105
2021-22*	1650000	138888.89	1709893	104
CAGR	**16.83**	**-**	**15.81**	**-**

Source: Ministry of Finance, Govt. of India, 2019-20.
* Data are provisional

Flow of agricultural credit from various financial institutes (scheduled commercial banks, cooperative banks, regional rural banks, other agencies including private banks, micro finance institutes etc.) are presented on Table 3. Scheduled commercial banks play a major role in disbursing agricultural credit with a compound annual growth rate of 20.21 per cent indicating that there exists a positive growth during the observed period. Over the years regional rural banks performs better in comparison with cooperative banks. Regional rural banks have compound annual growth rate of 21.37 per cent and cooperative have slightly lesser value of 12.06 per cent.

Table. 3: Institution wise flow of agricultural credit in India **(Rs in Crores)**

Years	Commercial Banks	Cooperative Banks	RRBs	Other Agencies
2000-01	27807 (52.46)	20718 (39.22)	4219 (7.99)	83 (0.16)
2001-02	33587 (54.13)	23524 (37.91)	4854 (7.82)	80 (0.13)
2002-03	39744 (57.16)	23636 (33.99)	6070 (8.73)	80 (0.12)
2003-04	52441 (60.29)	26875 (30.90)	7581 (8.72)	84 (0.10)
2004-05	81481 (65.02)	31231 (24.92)	12404 (9.90)	193 (0.15)
2005-06	125477 (69.52)	39404 (21.83)	15223 (8.43)	382 (0.21)
2006-07	166485 (72.57)	42480 (18.52)	20435 (8.91)	0 (0.00)
2007-08	181088 (71.11)	48258 (18.95)	25312 (9.94)	0 (0.00)

Years	Commercial Banks	Cooperative Banks	RRBs	Other Agencies
2008-09	228951 (75.83)	45966 (15.23)	26765 (8.87)	226 (0.07)
2009-10	285800 (74.33)	63497 (16.51)	35217 (9.16)	0 (0.00)
2010-11	332706 (74.47)	70105 (15.69)	43968 (9.84)	0 (0.00)
2011-12	368616 (72.13)	87963 (17.21)	54450 (10.65)	0 (0.00)
2012-13	432491 (71.21)	111203 (18.31)	63681 (10.48)	0 (0.00)
2013-14	509005 (71.53)	119963 (16.86)	82653 (11.61)	0 (0.00)
2014-15	604376 (71.50)	138469 (16.38)	102483 (12.12)	0 (0.00)
2015-16	604971 (68.94)	153295 (17.47)	119261 (13.59)	0 (0.00)
2016-17	799781 (75.04)	142758 (13.40)	123216 (11.56)	0 (0.00)
2017-18	871100 (74.93)	150300 (12.93)	141200 (12.15)	0 (0.00)
2018-19	954823 (75.97)	152340 (12.12)	149667 (11.91)	0 (0.00)
2019-20	1061215 (77.25)	149694 (10.90)	162857 (11.85)	0 (0.00)
2020-21	850543 (75.46)	133976 (11.89)	142603 (12.65)	0 (0.00)
CAGR	**20.21**	**12.06**	**21.37**	**-**

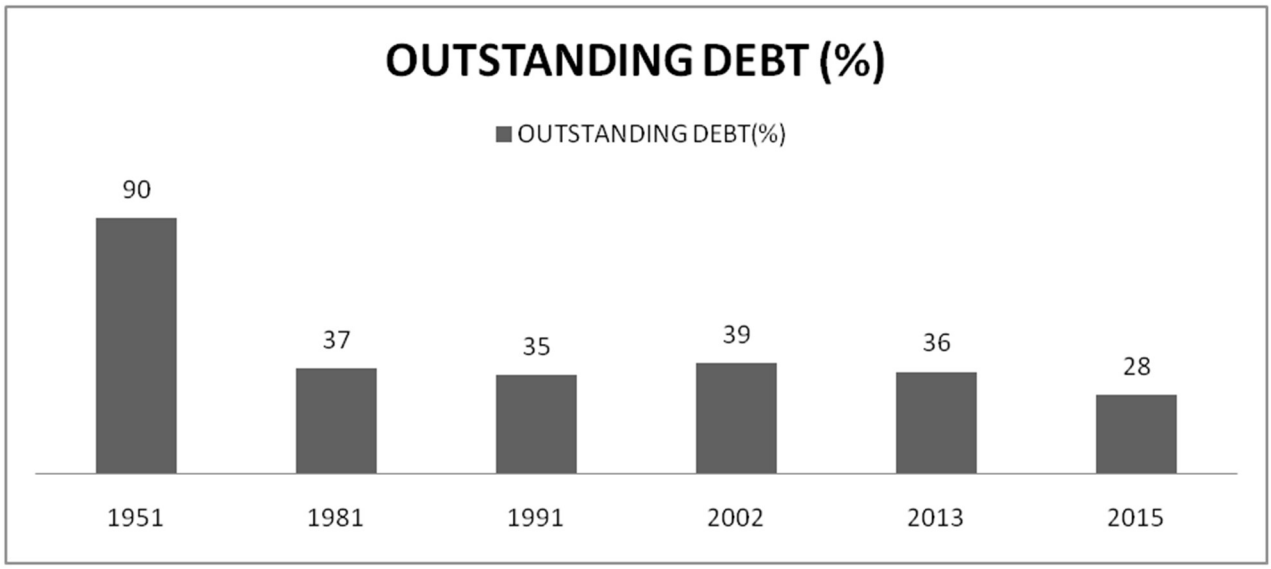
Figures in parentheses indicates percentage to total achievement

Source: Department of Agriculture, Cooperation and Farmer's welfare, Agricultural Statistics at a Glance (2020).

During 1950s, the agricultural credit needs were mainly obtained from non-institutional sources largely through local moneylenders. While the rural farmers had easy access to finance for their immediate needs, higher interest rates, coupled with high illiteracy levels and the subsequent lack of awareness put them into a spiraling debt trap leaving them at the mercy of the money-lender (RBI reports, 2019). From the Diagram 1, it is observed that during 1950s the non-institutional credit sources accounted for 90 per cent of the outstanding debt of cultivator households, but their share declined sharply to 37 per cent in 1981. After 1981, the rate of decline slowed down, and the share of non-institutional sources was 35 per cent in 1991. Thereafter a reversal of this pattern occurred which resulted in higher share of 39 per cent during 2002 which again dropped to 36 per cent in 2013. During 2015, the share of non-institutional credit was further decline at 28 per cent. This clearly indicates the over dependency to non-institutional sources mainly to local moneylenders

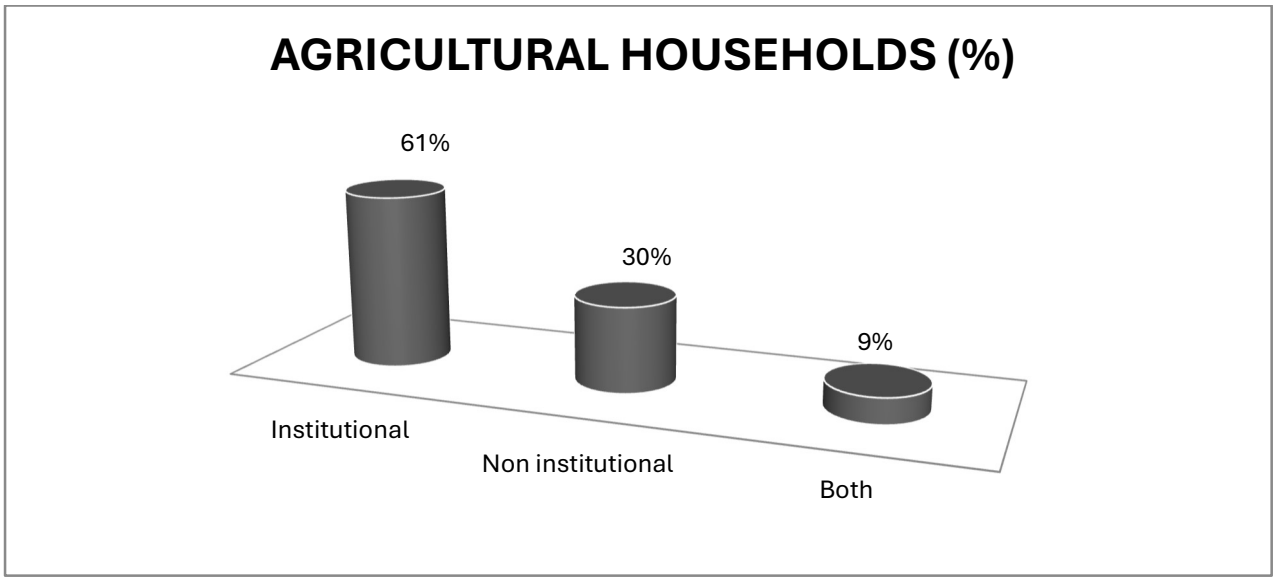
were gradually decreasing over the years. The evolution of the institutional structure through various Government policy interventions changed the scenario, whereby institutional credit sources, primarily through scheduled commercial banks became the major source for rural agricultural credit.

Diagram 1: Percentage share of outstanding debt (non-institutional) for cultivator household in India



Source: All India Debt and Investment Survey (2015), Government of India

Diagram 2: Distribution of agricultural households based on credit sources in India



Source: NABARD All India Rural Financial Inclusion Survey 2016-17.

It is evident from the Diagram 2 that, the majority of the agricultural households prefer institutional credit sources (61 per cent) to meet their financial requirements. However, still 30 per cent of the agricultural households depend on non-institutional sources for their requirement. The probable reasons maybe they belong to tenant farmers, sharecroppers and landless labourer who are unable

to offer collateral security to avail institutional credit, or they are involved in unviable subsistence agriculture or banks don't find them credit worthy. As a result, these farmers find it convenient to borrow money from non-institutional sources due to easy accessibility. Lastly, 9 per cent of the agricultural households depend on both institutional and non-institutional sources to meet their financial needs.

Table 4: State-wise credit disbursement to agriculture sector by Scheduled Commercial Banks in India during 2004-2022

Sl. No	Name of the state	Total amount (Rs in Crores)	CAGR (%)
1.	Haryana	540290	15.60
2.	Himachal Pradesh	70807	15.68
3.	Jammu And Kashmir	70823	22.22
4.	Punjab	762143	15.71
5.	Rajasthan	937886	18.50
6.	Arunachal Pradesh	2695	22.06
7.	Assam	116685	22.07
8.	Manipur	5972	30.10
9.	Meghalaya	8486	13.28
10.	Mizoram	4936	19.54
11.	Tripura	21153	23.62
12.	Nagaland	3463	30.39
13.	Bihar	430143	18.98
14.	Jharkhand	89880	18.49
15.	Orissa	239573	16.20
16.	West Bengal	424805	15.16
17.	Sikkim	1649	41.13
18.	Chhattisgarh	149751	17.31
19.	Madhya Pradesh	740820	16.61
20.	Uttar Pradesh	1479367	16.58
21.	Uttarakhand	94867	16.04
22.	Goa	10465	16.13
23.	Gujarat	657950	15.56
24.	Maharashtra	1163229	14.12
25.	Andhra Pradesh	1489589	15.15
26.	Karnataka	1171119	15.46
27.	Tamil Nadu	1819609	19.15
28.	Kerala	746614	19.53
29.	Telangana	509749	-
Union Territories			
1.	Chandigarh	67994	2.27
2.	Delhi	390277	7.78
3.	Ladakh	798	26.51

Sl. No	Name of the state	Total amount (Rs in Crores)	CAGR (%)
4.	Andaman and Nicobar Islands	1658	24.02
5.	Dadra & Nagar Haveli	618	37.33
6.	Daman & Diu	38	3.90
7.	Lakshadweep	50	14.14
8.	Puducherry	27071	32.34
	All India	14210223	**16.64**

Source: **Reserve Bank of India report, 2022.**

Volume of agricultural credits obtained by the small and marginal farmers widely differs from state to state in Indian Territory. From the Table 4, it is clearly seen that, major credit acquiring states includes Uttar Pradesh with compound annual growth rate of 16.58 per cent during the observed period, followed by Maharashtra (14.12%), Andhra Pradesh (15.15%), Karnataka (15.46%), Tamil Nadu (19.15%) and Rajasthan (18.50%), respectively. The least agricultural credits are received by the North Eastern states except Assam (Rs 1,16,685 Crores) with compound annual growth rate of 22.07 per cent during 2004-2022 and most of the Union Territories excluding Delhi (Rs 3,90,227 Crores) with a compound annual growth rate of 7.78 per cent during the observed period. The existing difference in the volume of credit taken is mainly due to difference in land acreage, higher level of farmers' participation, utilization of improved tools and modern techniques etc.

Conclusion

Ensuring that farmers have adequate access to financial resources is a key component for successful rural development strategies. Generally, farmers demand for two types of credit, one is considered as short-term credit to meet the current expenditure on seeds, fertilizer, insecticides, pesticides, hired laborer, transportation of harvested product to the farm houses, *etc.* and the other is long term credit to meet the capital expenditure on bullocks, power tiller, farm house, modern machinery, rent for leased in land, *etc*. Non-availability of timely credit has been a major drawback for the agricultural sector in India. In a country which mostly relies on agriculture, constant endeavors are needed to see that rural and agricultural facilities are enhanced with the passage of time. Without sufficient credit support, growth of agriculture cannot be accelerated particularly looking into the status of capital-starved farmers at large. Therefore, farm credit plays a game changer's role in redirecting the agricultural activities according to the needs and priorities of deprived farmers.

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METAL-ORGANIC FRAMEWORKS FOR SMART FOOD PACKAGING FROM SPOILAGE-GAS DETECTION TO REAL-TIME FRESHNESS MONITORING

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Highlights

- Metal-organic frameworks (MOFs) can be used to create advanced food packaging materials.
- MOFs can absorb important food-related gases and help control their levels, such as ethylene.
- MOF-based smart sensors can indicate food freshness by detecting spoilage gases such as ammonia and volatile amines.
- Colorimetric methods can indicate changes in food freshness through visible colour changes, helping to identify whether food is fresh or spoiled.
- Colour changes and sensor signals can be interpreted using smartphones, allowing rapid and convenient evaluation of food freshness.

Abstract

Food packaging systems are increasingly being developed not only to protect food but also to maintain quality and provide information about freshness, leading to the development of smart packaging systems (Zhang *et al*., 2025). Metal-organic frameworks have high porosity, adjustable structures and active surface areas, making them useful for intelligent food packaging (Hong *et al*., 2025; Chen *et al*., 2026). MOFs can adsorb food-related gases and provide antimicrobial and antioxidant functions (Hong *et al*., 2025; Zhang *et al*., 2025). MOF-based sensing systems can monitor food freshness through interactions with spoilage gases such as ammonia and volatile amines. These interactions can produce colour or optical changes that can be observed directly or analysed using smartphones. This review focuses on the role of MOFs in smart food packaging, including gas management, spoilage detection, freshness indication, sensing methods, safety concerns and future applications.

Keywords: Metal-organic frameworks; smart packaging; Spoilage gases; freshness monitoring; Food packaging.

Introduction

Food packaging plays a major role in protecting food from physical, chemical and biological factors and maintaining food quality and safety. Normally, packaging works as a protective or passive barrier, but it does not provide information about changes in food freshness during storage. Therefore, better methods are needed to monitor food quality, leading to the development of smart packaging systems that provide information about the condition of packaged food (Hong *et al*., 2025).

Metal–organic frameworks (MOFs) are porous materials formed by the combination of metal ions or clusters and organic linkers. They have a high surface area, adjustable pore structure and tunable

chemical properties, making them useful for food packaging applications. MOFs can interact with gases and other molecules and can therefore be used as gas adsorbents, antimicrobial materials and carriers for active compounds. For example, MOF-based systems have been studied for the adsorption of ethylene gas. Since ethylene promotes fruit ripening, reducing its level can slow fruit ripening and help extend shelf life (Sultana *et al*., 2022; Zhang *et al*., 2023).

MOFs are also being studied for food freshness monitoring. Sensing materials can be incorporated into MOF-based packaging systems to detect food spoilage gases such as ammonia and volatile amines. These interactions can produce colour changes, fluorescence or other measurable signals that can be used to identify variations in food freshness. Smartphone-based analysis can further help evaluate these signals quickly and conveniently (Hong *et al*., 2025).

Thus, MOF-based packaging provides an opportunity to combine food preservation and freshness monitoring in a single packaging system. This article describes the role of MOFs in smart food packaging, with a focus on spoilage-gas management, active packaging, freshness detection, sensing strategies, practical challenges, safety concerns and future applications.

MOFs and Their Properties for Food Packaging

Metal–organic frameworks (MOFs) are porous materials with high porosity, large surface area, variable pore structures and adjustable surface properties. These characteristics allow MOFs to interact with gases and other molecules, making them useful for different food packaging applications (Hong *et al*., 2025; Chen *et al*., 2026).

MOFs can be incorporated into polymeric or biopolymer films to provide gas sorption, antibacterial activity and controlled release of active compounds. Their ability to interact with specific molecules can also be used to develop sensing packages for monitoring food quality and freshness (Hong *et al*., 2025). Therefore, MOFs can support multifunctional smart packaging systems combining food preservation, gas management and freshness monitoring.

MOFs for Spoilage-Gas Recognition and Active Packaging

MOFs can interact with gases and microorganisms through their porous structures and active sites. One important example is ethylene, a plant hormone that accelerates fruit and vegetable ripening. MOF-based materials have been studied for ethylene adsorption, which can slow ripening and extend the shelf life of fresh produce (Sultana *et al*., 2022; Zhang *et al*., 2023).

MOFs can also provide antimicrobial and antioxidant properties when incorporated into composite films or MOF–polymer membranes. These materials can help reduce microbial growth and oxidative deterioration, providing additional protection to food (Hong *et al*., 2025).

Overall, MOF-based active packaging can help manage factors related to food deterioration, particularly ethylene and microbial activity, thereby supporting food quality and shelf life.

MOFs for Freshness Monitoring

MOFs can monitor food freshness by detecting gases produced during spoilage, mainly ammonia and volatile amines. These gases are important indicators of freshness in protein-rich foods such as meat and seafood. As spoilage progresses, their concentration generally increases, and MOF-based sensing films can respond with measurable signals (Hong *et al*., 2025).

Ammonia and Volatile Amine Sensing

MOFs can be combined with indicator materials or other sensing components to develop films for detecting ammonia and volatile amines. Interaction with these gases can cause colour or

fluorescence changes that indicate the freshness condition of packaged food. For example, a 2025 study developed a cellulose acetate/curcumin-loaded CD-MOF film that showed ammonia-sensitive colour changes and was applied to monitor shrimp freshness (Hu and Tan, 2025).

Colour-Based Freshness Indication

Colorimetric sensing is a simple method for indicating food freshness and generally requires little or no complex instrumentation. In MOF-based smart packaging, sensing materials can change colour when they interact with spoilage gases. Consumers can observe these changes without opening the package and obtain an indication of food freshness. Recent studies have developed MOF-based colorimetric films for ammonia detection and freshness monitoring of shrimp and other protein-rich foods (Hu and Tan, 2025).

From Gas Detection to Real-Time Monitoring

MOF-based sensing systems can provide food freshness information through visible colour changes or other measurable signals. Smartphones can analyse these signals, making freshness monitoring more rapid and convenient. A smartphone camera can capture the colour or optical response of a sensing film, while image-analysis applications can evaluate the changes to provide an indication of food freshness.

Smartphone-assisted sensing can reduce the need for complex laboratory equipment and support rapid freshness monitoring of perishable foods such as meat, seafood and fresh-cut fruits. However, lighting conditions, differences between smartphone cameras, sensor calibration, colour-analysis methods and standardization need to be considered for reliable results. Thus, combining MOF-based sensing films with smartphone analysis provides an approach for moving from simple spoilage-gas detection to rapid and convenient real-time food freshness monitoring.

Comparison of Recent MOF-Based Smart Packaging Studies

MOF-based system	Food/Application	Function	Packaging response	Major outcome
Mg-formate MOF/LDPE	Banana and fresh produce	Ethylene adsorption	Reduction of ethylene around the produce	Delayed banana ripening and extended shelf life
HKUST-1/cellulose acetate	Veal, fish and chicken	Ammonia detection	Colourimetric response analysed using a smartphone	Enabled portable and non-destructive spoilage monitoring
Co-MOF/sodium alginate	Shrimp	Ammonia detection and antimicrobial activity	Visible ammonia-sensitive response	Successfully monitored shrimp freshness
Zn-MOF/PVA–starch	Shrimp	Colour/fluorescence	Colour/fluorescence	Real-time monitoring

MOF-based system	Food/Application	Function	Packaging response	Major outcome
Alizarin/Zn-MOF/PVA hydrogel	Shrimp	Amines + pH	Yellow–purple + smartphone	Rapid freshness evaluation
Co-BIT/cellulose acetate	Smart food packaging	Ammonia + antibacterial	Sensitive film	Better packaging properties

Table 1. Applications of MOF-based smart packaging for food freshness monitoring

Source: Compiled from Zhang *et al*., (2023), Hashemian *et al*. (2023), Feng *et al*., (2023), Kang *et al*., (2025) and Zhang *et al*., (2025).

Future Perspectives

Future research on MOF-based smart packaging should focus on stable, biocompatible and environmentally friendly MOFs for food-packaging applications. Combining MOF-based sensor films with smartphones and artificial intelligence (AI) can support faster and more accurate freshness monitoring. Research should also focus on cost-effective manufacturing, moisture stability and practical food-contact safety to support wider application**.**

Conclusion

MOF-based smart packaging offers an approach for combining food preservation with real-time freshness monitoring. The porous and tunable properties of MOFs enable interaction with food-related gases such as ethylene, ammonia and volatile amines, making them useful for controlling deterioration and detecting spoilage-related changes. The integration of MOF-based sensing films with colourimetric indicators, smartphones and artificial intelligence can provide rapid freshness information without opening the package. However, migration, toxicity, moisture stability, production cost and food-contact safety remain important challenges. Stable, biocompatible and environmentally friendly MOF-based systems with standardized safety evaluation are needed for practical application.

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GENETIC IMPROVEMENT OF ASAFOETIDA (*Ferula assa-foetida* L.): A CONCISE REVIEW AND BREEDING FRAMEWORK FOR INDIA

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Abstract

Asafoetida (*Ferula assa-foetida* L.) is a high-value, perennial, monocarpic member of Apiaceae whose root-derived oleo-gum-resin (heeng) is an important spice and medicinal raw material. Genetic improvement has lagged behind its economic importance because of persistent seed dormancy, a long juvenile phase, monocarpic reproduction and limited germplasm characterization. Recent studies, however, provide a strong foundation for a breeding programme: molecular markers have revealed high genetic diversity, accession trials have identified useful variation in dormancy and germination, floral-biology studies from the Indian Himalaya have clarified breeding behavior and proteomic, transcriptomic and tissue-culture studies have begun to reveal the molecular basis of germination and resin-related metabolism. This article synthesizes this evidence and proposes a concise breeding framework for India built around germplasm conservation, dormancy reduction, rapid tissue-culture-assisted multiplication, resin yield and quality and multi-environment evaluation, with molecular markers and genomic selection as medium-term accelerators.

Keywords: Asafoetida; *Ferula assa-foetida*; heeng; seed dormancy; tissue culture; resin yield; molecular diversity

Introduction

Asafoetida, commonly known as heeng, is valued across Central and South Asia for its root-derived oleo-gum-resin. Its cultivation and improvement have been constrained by persistent seed dormancy, poor germination, a multi-year juvenile phase and limited high-yielding planting material (Kumar *et al*., 2024; Salehi *et al*., 2019). Because plants may take several years to flower and reproduce only once, conventional phenotypic selection is slow and costly, making early-stage screening and molecular tools especially valuable. Recent work on molecular diversity (Tajbakht *et al*., 2018), reproductive biology under Indian conditions (Rana *et al*., 2026), seed dormancy (Kumar *et al*., 2025), and tissue culture (Patial *et al*., 2026) together provide a practical foundation for a dedicated breeding programme, summarized here.

Genetic Resources and Reproductive Biology

A national base collection should combine wild populations, introduced material and Indian-maintained accessions, with passport data on origin, altitude and climate. Molecular studies using SCoT and SRAP markers on 64 accessions from 12 Iranian populations revealed very high polymorphism (92-96%) and substantial within-population diversity that was not simply explained by geography (Tajbakht *et al*., 2018), a pattern corroborated by ISSR-based differentiation studies (Jafari *et al*., 2019). This indicates considerable untapped breeding potential and argues for a core collection built on molecular and geographic diversity rather than visual selection alone.

F. assa-foetida is monocarpic and andromonoecious, with floral dimorphism and protandry. Floral-

biology work under Indian Himalayan conditions found rapidly declining pollen viability, spatially restricted pollen dispersal and insect-mediated outcrossing (Rana *et al*., 2026). For controlled crossing this means pollen must be collected fresh at peak viability, flowering must be synchronized across parents and pollinated umbels should be bagged and replicated technically demanding but feasible.

Seed Dormancy and Germination

Persistent seed dormancy is the most immediate barrier to breeding, reducing effective population size and nursery efficiency. Cold stratification (4-5°C) is consistently the most effective dormancy-breaking treatment and its effect can be enhanced by gibberellic acid (GA_3), although accessions differ in their hormonal response (Kumar *et al*., 2025). Proteomic and metabolomic profiling of cold-stratified seeds has identified over 200 proteins and nearly 100 metabolites associated with dormancy release, involving signalling, energy metabolism and ROS-scavenging pathways (Punia *et al*., 2024) a resource that could be mined for early, seedling-stage selection markers rather than waiting years for mature-plant phenotyping. A standard breeding-screening protocol should record viability, stratified and unstratified germination, mean germination time, T50, seedling vigour and post-transplant survival across seed lots and years to separate genetic from maternal effects.

Resin Yield, Quality and Tissue Culture

Oleo-gum-resin yield is the principal economic target and is a complex trait influenced by genotype, root development, environment and harvesting method, with clear genotype and environment effects on yield and essential-oil composition (Moghaddam and Farhadi, 2015). Candidate genes for terpenoid and phenylpropanoid biosynthesis have been identified through tissue-specific transcriptomics (Amini *et al*., 2019) and a recent review of gum and resin biosynthesis across *Ferula* (Karimi *et al*., 2024) supports treating resin quantity and chemistry as a genetically tractable, pathway-linked target rather than a purely environmental outcome.

Tissue culture is an important enabling technology for a monocarpic, slow-establishing crop. Direct somatic embryogenesis has been demonstrated from root, hypocotyl and cotyledon explants (Roozbeh, 2012) and a recent reproducible micropropagation system combining leaf-derived callus, somatic embryogenesis and molecular/flow-cytometric fidelity testing offers a practical route to multiply elite genotypes true-to-type (Patial *et al*., 2026). In vitro elicitation (e.g., UV-C) of friable callus has also been shown to alter expression of resin-pathway genes, suggesting callus systems can support early biochemical screening in addition to multiplication (Kumari *et al*., 2026). The key breeding principle is that tissue culture should preserve and multiply genotypes already validated for high resin yield across environments, not be used as a substitute for that validation.

Proposed Breeding Framework for India

Breeding priorities for Indian conditions are: (i) reduced seed dormancy and rapid, uniform germination, (ii) fast seedling establishment and high transplant survival, (iii) high and stable oleo-gum-resin yield and quality (iv) adaptation to Himalayan production zones and climatic stresses; and (v) reliable flowering and seed production.

Stage	Focus	Key outputs
1. Germplasm assembly & characterization	Collect Indian/introduced accessions; molecular and phenotypic profiling	Core collection; contrasting parents

Stage	Focus	Key outputs
2. Dormancy screening & crossing	Standardized stratification protocols; synchronized controlled crosses	Low-dormancy families; F1 seed
3. Multiplication & multi-environment testing	Tissue-culture multiplication of elite types; trials across Himalayan sites	Stable, adapted selections
4. Quality selection & release	Standardized resin/essential-oil profiling; genomic-marker validation	Elite genotype(s) for release

Table 1. Condensed four-stage breeding framework for asafoetida in India

Molecular breeding should progress in parallel: a diversity panel of 200-500 accessions genotyped by SNP markers can support genome-wide association studies for dormancy and resin traits, feeding eventually into genomic selection so that breeding values can be predicted in juvenile plants rather than after years of field evaluation. This is particularly valuable for asafoetida given its long generation interval.

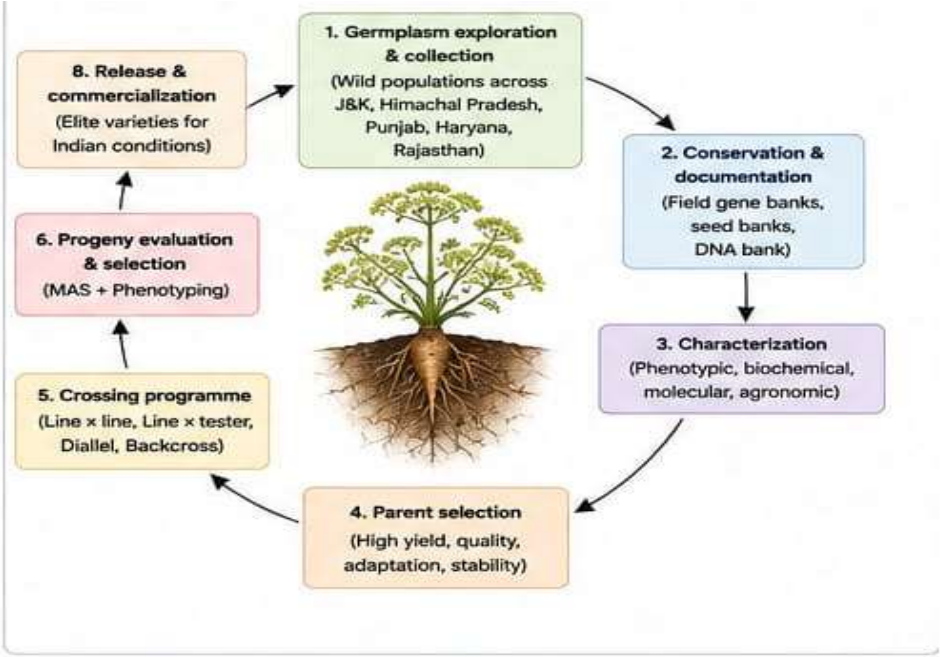


Fig.1: Proposed Indian breeding programme for asafoetida

Conclusion

Asafoetida breeding in India can now move beyond ad hoc domestication toward a coordinated programme. The priorities are a well-characterized, diverse germplasm base; reliable dormancy-breaking and nursery protocols; a technically sound controlled-crossing system; tissue-culture-based multiplication of validated elite genotypes and multi-environment evaluation of resin yield and quality, supported over the medium term by molecular markers and genomic selection. Integrating these elements into a single pipeline, rather than treating seed biology, tissue culture and resin chemistry as separate problems, is the most direct route to a genetically improved, sustainable asafoetida crop for Indian Himalayan production systems.

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MICROPLASTICS IN SEAFOOD: AN EMERGING CHALLENGE FOR FOOD SAFETY AND SUSTAINABLE FISHERIES

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Abstract
Plastic pollution has become one of the major environmental challenges affecting aquatic ecosystems. As larger plastic materials undergo weathering, fragmentation and degradation, they generate small particles known as microplastics. These particles are increasingly reported in marine, brackish and freshwater environments and have been detected in commercially important fish, crustaceans and molluscs. Seafood may therefore represent one pathway through which humans are exposed to microplastics. The occurrence of microplastics in seafood is influenced by environmental contamination, feeding behaviour, habitat, species characteristics and fishing or aquaculture-related activities. Microplastics may also interact with chemical contaminants and microorganisms present in the aquatic environment. However, detection of microplastics in seafood should not automatically be interpreted as evidence of a direct health hazard to consumers, as human exposure levels and toxicological consequences remain incompletely understood. This article discusses the sources, pathways and occurrence of microplastics in seafood, potential food-safety implications, analytical challenges and strategies for reducing plastic contamination throughout the aquatic food chain. Strengthening monitoring, standardizing analytical methods, reducing plastic leakage and adopting a One Health approach are essential for protecting aquatic ecosystems and maintaining consumer confidence in seafood.

Keywords: Microplastics, seafood, fishery products, food safety, plastic pollution, aquatic ecosystem, One Health

Introduction

Plastic has transformed modern life because of its versatility, durability, light weight and low cost. These same properties, however, make plastic persistent in the environment. Large quantities of plastic waste enter terrestrial and aquatic environments every year, where larger plastic items can gradually fragment into smaller particles.

Particles generally described as microplastics are smaller than 5 mm. They can originate as small manufactured particles or arise from the fragmentation of larger plastic products. Their presence has been documented in rivers, estuaries, coastal waters, oceans and sediments. Consequently, aquatic organisms may encounter these particles throughout their life cycle.

Seafood is an important component of the human diet and provides high-quality protein, omega-3 fatty acids, vitamins and minerals. Fish, shellfish and other aquatic organisms may, however, ingest microplastics present in their surrounding environment. Recent systematic evidence has documented microplastic contamination in fish, crustaceans and molluscs from different geographical regions. A 2024 systematic review reported substantial variation in the size, polymer

type, shape and colour of particles detected in seafood, reflecting differences among environments and analytical approaches (Woh et al., 2024).

The issue therefore lies at the intersection of environmental pollution, fisheries, food safety and human health**.**

Sources of Microplastics in Aquatic Ecosystems

Microplastics can enter aquatic environments through both land-based and marine activities. Important sources include:

- Fragmentation of plastic bags, bottles, packaging and fishing materials
- Synthetic textile fibres released during washing
- Domestic and industrial wastewater
- Urban stormwater runoff
- Agricultural runoff
- Improper disposal of plastic waste
- Degradation of fishing nets, ropes and other fishing equipment
- Plastic materials used in aquaculture
- Atmospheric deposition

Once released into water bodies, microplastics can be transported by currents, accumulate in sediments or remain suspended in the water column. Their distribution is influenced by particle density, shape, size, surface characteristics and environmental conditions.

How Do Microplastics Enter Seafood?

Aquatic organisms can encounter microplastics through several routes. Fish may accidentally ingest particles while feeding, particularly when microplastics resemble natural prey. Filter-feeding organisms such as mussels and oysters can accumulate particles while filtering large volumes of water.

Microplastics can subsequently move through aquatic food webs. Predatory organisms may consume contaminated prey, providing another possible pathway of exposure.

However, the detection of microplastics in an aquatic organism does not necessarily mean that the particles are present in the edible portion consumed by humans. This distinction is particularly important for fish because particles may be concentrated in the gastrointestinal tract rather than the muscle tissue.

Therefore, food-safety studies should clearly differentiate between:

Microplastics present in the digestive tract → environmental exposure
and
Microplastics present in edible tissues → potential dietary exposure.
This distinction is essential when estimating actual human exposure.

Microplastics Reported in Commercial Seafood

Studies have reported microplastics in a wide range of seafood species. Fish, crustaceans and molluscs have all been investigated. A recent systematic review found that reported particles differed considerably in size, polymer composition, shape and colour. Among the reported characteristics, particles in the 100–1500 µm range, polyethylene terephthalate polymers and fibrous particles were frequently represented in the available literature (Woh et al., 2024).

Another review of fish and fishery products highlighted that seafood can contribute to human dietary exposure to microplastics, while also emphasizing that available evidence remains insufficient for a reliable assessment of the overall human health risk (Alberghini et al., 2023).

Such variation demonstrates why comparing microplastic concentrations between studies can be difficult. Different researchers may use different sampling locations, fish species, digestion procedures, particle-size limits and identification techniques.

Potential Food-Safety Concerns

Microplastics are not simply inert particles. Their potential significance is related to several characteristics.

First, some plastic materials contain chemical additives introduced during manufacturing. Second, microplastics can interact with contaminants present in the surrounding environment because of their surface characteristics. Third, microorganisms can colonize their surfaces, creating what is sometimes referred to as a plastisphere.

Experimental research has investigated possible biological effects including oxidative stress, inflammation, cellular damage and interactions with biological membranes. However, laboratory findings should not automatically be interpreted as demonstrating the same effects at the levels encountered through normal seafood consumption.

The World Health Organization has emphasized substantial uncertainties surrounding exposure and health effects and has identified the need for additional research, particularly regarding realistic environmental exposure and toxicological effects (WHO, 2022).

Therefore, the scientifically appropriate message is not that seafood is inherently unsafe because microplastics have been detected. Rather, microplastics represent an emerging contaminant requiring continued monitoring and risk assessment**.**

Microplastics and Seafood Processing

Seafood processing may influence microplastic occurrence and exposure in different ways. Washing, gutting, filleting, cooking and other processing operations can potentially alter the distribution of particles.

For whole fish, the gastrointestinal tract may be removed during processing, potentially reducing exposure to particles concentrated in the digestive system. In contrast, products prepared from whole small fish or organisms consumed with edible viscera may require particular attention.

Packaging and processing environments are also relevant. Plastic equipment, containers and packaging materials may represent potential sources of contamination if not properly controlled.

Consequently, future studies should investigate microplastics across the entire seafood supply chain—from harvesting and aquaculture to processing, packaging, distribution and consumption.

Challenges in Microplastic Detection

One of the major challenges is the absence of complete standardization in sampling and analytical procedures.

Microplastics vary in:

- Size
- Shape

- Polymer type
- Colour
- Density
- Surface characteristics

Common analytical approaches include microscopic examination followed by chemical identification using techniques such as Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy.

Sample preparation is equally important. Organic matter must often be removed before particle identification. Contamination from airborne fibres, laboratory equipment and plastic materials used during analysis can also affect results.

Therefore, strict quality-control procedures and harmonized analytical protocols are essential.

Towards Safer and More Sustainable Seafood

The most effective way to address microplastic contamination is to reduce plastic leakage into aquatic ecosystems at the source.

Important measures include:

1. Improved collection and recycling of plastic waste.
2. Reduction of unnecessary single-use plastics.
3. Better wastewater treatment.
4. Responsible management of fishing gear.
5. Recovery and recycling of damaged fishing nets and ropes.
6. Improved plastic management in aquaculture.
7. Regular monitoring of seafood from potentially contaminated environments.
8. Development of standardized analytical methods.
9. Consumer awareness regarding responsible plastic disposal.
10. Greater collaboration between fisheries, environmental and food-safety authorities.

The fisheries sector can play an important role by promoting responsible fishing practices, reducing abandoned or lost fishing gear and adopting more sustainable materials wherever feasible.

One Health Perspective

Microplastic pollution cannot be considered solely an environmental problem. It involves the interaction of environmental quality, animal health and human food safety.

The One Health approach provides a useful framework because it recognizes the interconnectedness of humans, animals and ecosystems. Monitoring microplastics in water, sediments and aquatic organisms can therefore provide information relevant to both ecosystem health and food safety.

Researchers from fisheries science, food technology, environmental science, toxicology and public health need to work together to generate reliable evidence.

Future Perspectives

Future research should move beyond simply reporting the number of particles detected in seafood. Greater attention should be given to:

- Microplastics in edible muscle and other tissues

- Nanoplastics and their detection
- Effects of cooking and processing
- Long-term dietary exposure
- Polymer-specific toxicity
- Interactions with chemical contaminants
- Effects on commercially important Indian seafood species
- Standardized risk-assessment approaches
- Development of low-plastic and circular seafood supply chains

India, with its extensive coastline, diverse aquatic resources and large seafood sector, has an important role in developing region-specific data on microplastic contamination.

Conclusion

Microplastics represent an emerging challenge for aquatic ecosystems and seafood safety. Their widespread environmental distribution and detection in fishery products demonstrate the close relationship between plastic pollution and food systems. Nevertheless, current scientific evidence does not justify assuming that the presence of microplastics in seafood automatically results in a specific human health outcome. Significant uncertainties remain concerning exposure levels, particle characteristics, absorption and long-term effects.

The priority should therefore be prevention, monitoring, standardized detection and evidence-based risk assessment**.** Reducing plastic pollution at its source will simultaneously benefit aquatic biodiversity, fisheries sustainability and food safety. A coordinated One Health approach involving scientists, fishers, processors, policymakers and consumers can help build cleaner aquatic environments and safer seafood systems.

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CHALLENGES AND INNOVATIONS IN MULTILAYER PACKAGING: TOWARD SUSTAINABLE AND RECYCLABLE SYSTEMS

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Abstract

The multilayer packaging technology has played a very important role in the food and consumer goods industries globally due to its excellent barrier properties, mechanical strength, and product preservation abilities. However, the existence of different layers of polymers, metals, and adhesives and their individual difficulties still pose a strong challenge to recycling and environmental management. The components are so tightly bound together that sometimes the recycling process turns out to be ineffective, and the end products are either sent to landfills or incinerated. However, the newest technologies like advanced chemical recycling, solvent-based delamination, and compatibilization have greatly relieved the problem of purifying polymers. Moreover, the technologies of single-material system design, nano-composite coatings, and biodegradable and renewable materials are all forcing the packaging industry to be sustainable. Despite these technological advancements, food safety and regulatory compliance remain the top obstacles especially regarding the potential for contaminants migration and the absence of internationally accepted standards. In near future, the principles that promote reuse and recovery of materials instead of disposal, combined with extended producer responsibility schemes and smooth global regulations will pave the way for the widespread adoption of recyclable multilayer systems. The next generation of packaging materials that are intelligent, eco-friendly, and responsible users of resources will be created by the three dimensions of performance, safety, and environmental sustainability being carefully balanced.

Keywords: Bio-based Polymers, Chemical Recycling, Multilayer Packaging, Recycling Technologies, Solvent-Based Delamination, Sustainable Packaging.

Introduction

The multilayer packaging method is considered one of the best options available to ensure that products maintain their quality and consumer markets have them for a longer time. In general, it is a combination of several different materials such as plastics, metals, and paper, where each material has its own properties like strength, flexibility, and barrier resistance. Consequently, the layers create a very efficient system that protects the products from air, light, moisture, and microbes while allowing the products to be fresh during storage and shipping. The flexibility of the multilayer films makes them highly suitable for the food, pharmaceutical, and consumer goods markets.

However, this breakthrough has also been a cause for major environmental and recycling problems. The use of adhesives and coatings to bring different materials together renders the separation of these materials very difficult when they are no longer needed. Multilayer structures, as opposed to the mono-material ones, are not compatible with the current recycling technologies as they do not

yield to the conventional processing and they often end up in landfills or being incinerated. This results not only in pollution but also in contradiction to the global demand trend towards circular economy practices. Accordingly, the scientific community and industry are collaborating closely to render these materials eco-friendly yet maintain their performance capabilities.

Modern chemical recycling techniques like solvent-based delamination, compatibilization etc., have demonstrated that the recycling of high-performance polymers from multilayer waste streams is profitable and environmentally friendly. Moreover, the creation of biodegradable and recyclable multilayer substrates with superb barrier properties is made possible through the incorporation of biodegradable and renewable materials and nano-composite coatings innovations. The former is being pushed by new regulations and global initiatives to sustain the planet which are targeting the reduction of plastic waste and carbon emissions.

The primary challenge now is that of making high-performance packaging compatible with the characteristics of recyclability and safety. Consequently, the focus has shifted to the production of smart materials that are both eco-friendly and safe for use, offering protection, and adaptability, and being compliant simultaneously. The development of multilayer packaging has turned out to be not just a challenge of engineering prowess but also a matter of global consciousness towards a safer and more sustainable future.

Current Challenges in Multilayer Packaging Recycling

Multilayered packaging is considered an important feature in the food and consumer goods industries due to its excellent barrier properties and mechanical strength. It has become the standard for these industries. Manufacturers arrange different plastics, metals, and papers in layers to effectively block all harmful elements such as oxygen, moisture, and light, thereby enhancing the durability of the products. However, multilayer construction has also played a big part in contributing to the packaging industry's pollution problems. The layers become glued together with adhesives and coatings, turning into a single material, which makes the recycling of such substances very inefficient and sometimes even impossible.

Conventional recycling facilities are restricted to processing only single-material plastics. When multilayer films containing polyethylene, polypropylene, and PET, or even aluminum are introduced into the recycling stream, the process is contaminated, and hence the quality of recyclates is low. It gets even more difficult with the adhesives, printing inks, and coatings that are used for both functional and aesthetic reasons since these materials are hindering melting and reprocessing. So, the output is a less valuable product with a short range of applications and a low market price. The issue of polymers' incompatibility in multilayer composites is the main factor behind the poor recyclability and quality degradation of post-consumer waste streams.

In addition to the technological hurdles, the limited availability of reliable recycling infrastructure aggravates the situation. The majority of countries lack specialized facilities for separating and reprocessing composite packaging and hence, the dumping of such materials into landfills or burning occurs on a large scale. The aforementioned remedies are accountable for both resource exhaustion and pollution of the ecosystem. Moreover, multi-layered packaging comes with a larger carbon footprint than mono-material options because of its difficulties and issues relating to the recyclability. The question of economic viability remains a serious hurdle. The application of modern technology such as chemical depolymerization or solvent-based delamination would yield high-

quality recovery of pure materials but the high purity also means high costs. The reasons for that include large energy consumption and the need for sophisticated equipment. Without the necessary legislation, either by providing incentives for recycling or creating a large market for recycled polymers, the companies will have very few reasons to massively adopt such technology. The instability in policies is yet another hurdle that is always in the way. In some parts of the world, there are very ambitious recycling targets and the introduction of EPR schemes, while in other areas there are practically no regulations. This disparity in implementation not only causes the process to be slower but also makes it difficult for the players to come together and develop a unified recycling scheme. Thus, the shift towards a circular economy is still very slow and random.

Technological Advances in Recycling and Material Recovery

The recycling of multilayer packaging is still a challenge, but nevertheless, it has now been made possible to get the valuable polymers through chemical processes, compatibilization methods, and redesigning of the materials. These recycling methods not only increase the efficacy of the recycling process but also facilitate the global change to a circular economy. Chemical recycling has the power to become one of the most effective technologies for multilayer packaging recovery. Instead of just re-melting and reforming materials as done in mechanical recycling, advanced chemical recycling breaks down the polymers to their chemical building blocks: monomers, oligomers, or hydrocarbons that can then be purified and repolymerized into high-quality new plastics. The technologies such as pyrolysis, glycolysis, and depolymerization respectively allow the extraction of the compounds from mixed or contaminated plastic waste that would otherwise be classified as non-recyclable. One more solvent-based chemical method is better in detoxifying and reclaiming adhesives and coatings, doing it layer-by-layer, and each time recovering the one without much loss of quality. The application of such technology has demonstrated that it is possible to have high-purity polymers that can be reused in new packaging systems.

Along with advanced chemical recycling, researchers have proposed methods based on compatibilizers that are specifically intended to improve mechanical recycling performance. Compatibilizers are materials that, by their presence, create stronger interactions among incompatible polymers, thus resulting in a more homogeneous mixture and better quality recycled products. Still, this technique does not completely solve the issue of layered separation but instead extends the life cycle of the material through the production of quality recyclates from multilayer wastes. These days, such breakthroughs in nanotechnology and coating techniques have already made notable contributions to the area of material recovery. The combination of nanoclays, nanocellulose, and metal oxide nanoparticles with polymers has resulted in the fabrication of barrier materials that are very good and would otherwise have to be made from multi-layer or composite materials, not to mention the use of other resources. The shift toward single-material system design reduces not only the recycling process but also the risk of contamination. In the same way, ultra-thin barrier coatings that are applied by using techniques such as plasma-enhanced or atomic layer deposition can now take the place of non-recyclable aluminum layers without affecting the quality of the end product.

The eventual rise of reversible adhesive systems which are capable of being unfixed again has become a significant point of transition in the packaging design aimed at recycling. Under some conditions, these adhesives make it possible to open the layers of packaging for separation and reprocessing. It is very probable that the mixture of eco-friendly materials, cutting-edge recycling

technologies, and innovative approaches will lead to the development of new and superior environmentally friendly packaging solutions. Even though these technologies are not fully developed, they are already recognized as a remarkable step forward in finding an appropriate compromise between product safety and performance and recyclability. Interdisciplinary collaboration and research efforts involving industry, public policy, and academia will be the principal reason for the transformation of these laboratory conquests into much broader application.

Innovative Approaches for Sustainable Multilayer Packaging

The environmental impact of multilayer packaging has, however, continuously increased, which has led to the industry side changing its strategies to combine sustainability with high performance. The traditional multilayer structures have been using polymers, metals, and adhesives with the intention of making barriers against oxygen, light, and moisture; but the complexity of the designs makes recycling impossible. The companies are starting to change their marketing strategies by adopting eco-design principles, and they are beginning to use safer and more recyclable materials for food contact.

One of the major breakthroughs is the mono-material multilayer design mainly consisting of one type of polymer such as polyethylene (PE) or polypropylene (PP) for the entire package. The necessary mechanical and barrier properties are realized through thin coatings or surface modifications, hence the compatibility with the existing recycling streams. State-of-the-art coatings like silicon oxide or aluminum oxide applied through plasma-enhanced techniques give these mono-materials performance similar to that of conventional multilayers.

The introduction of bio-based and biodegradable polymers has been the industry`s major turning point. Among the various types, Polylactic Acid (PLA) and Polyhydroxyalkanoates (PHAs) are the most popular and widely used ones. By using nanocellulose or nanoclays reinforcement, these materials are not only getting stronger but also more efficient as barriers. Additionally, switchable adhesive systems and reversible laminations have made it possible to easily separate layers after use, thus saving energy and promoting recycling along with other circular economy practices.

The combination of these developments is leading to the gradual phase-out of the traditional multilayer packaging that has been the main contributor to waste and the establishment of a new sustainable and resource-efficient system.

Safety and Regulatory Consideration in Multilayer Recycling

Recycling technologies have progressed remarkably, nevertheless, food safety and compliance with regulations are the major hindrances to the use of recycled multilayer packaging on a large scale. Absolute disposal of all those dealing with food materials non-compliance either through international safety standards or health risks resulting from chemical residues, solvents, or nanoparticles leaching into food is a must.

Mainly, the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) are the two organizations that handle such food-contact application materials' evaluations. Both require the very extensive testing to be done first to confirm that no harmful substances are present beyond the permissible limits. The concern is most significant for the multilayer recycled polymers where the adhesives, inks, and coatings may leave the impurities that are almost impossible to wipe out completely.

Chemical recycling can yield very pure polymers while at the same time introducing safety problems due to the presence of solvents and catalysts. Similarly, the increased use of nano-materials in packaging has led to the introduction of regulations that will ensure the safety of these materials in food-contact areas by controlling migration or chemical changes that might lead to instability and thus, preventing the use of such materials.

The lack of compatible global regulations makes the situation even more complicated. A universally accepted safety framework and traceability systems would not only make the approval process quicker but also enhance consumer trust and speed up the approval of recycled materials. Scientific validation, transparent labeling, and consistent regulation will enable the packaging industry to achieve its long-term sustainability goals without compromising public health.

Future Prospect and Circular Economy Alignment

The multilayer packaging recycling is surely going to be subjected more and more to the requirements of the circular economy that aim at keeping materials in productive use for as long as possible while at the same time reducing waste to a minimum and thus the rules of the circular economy are determining the recycling future of multilayer packaging more and more. The consumer and industrial sectors have already switched their priorities to sustainability and consequently manufacturers appear to be investing their efforts in the constant progress of material and systems that allow full recyclability, reuse, and resource efficiency. The blending of the circular principles and the design of the packaging not only makes it easy to recover the materials at the end of the life cycle but also results in the reduced consumption of fossil-based raw materials and reduced greenhouse gas emission.

In the next few years, it is anticipated that chemical and solvent-based recycling methods will usher in a significant change to the material-loop-closing process. These recycling techniques can allow the re-entry of recycled polymers into the production cycle of packaging without the fear of safety and quality being compromised by relying on the extraction of top-quality feedstocks from complex waste streams. Besides, they are compatible with the design of single-material systems, the use of reversible adhesive systems, and the creation of packaging with improved resistance to oxygen, moisture, and light which is not only sustainable but also economically viable. The collaboration between policies and industry participation in equal measure will be the forces of the transition to come. EPR programs combined with clear recyclability labels will make it hard for producers not to be responsible and, at the same time, will help consumers make sure their disposal methods are right. In the meantime, development of recycling infrastructure and providing life cycle assessment tools are going to be very important for ensuring that recovery processes of materials are not only profitable but also very eco-friendly.

The alignment of the material science, advanced recycling, and circular policy frameworks is probably going to give a new perspective to the packaging sector. The goal is to establish a packaging system based on recycling where the materials are never-endingly reused or multilayer structures where no longer waste but renewable resources are continuously circulated, thus, driving the actual sustainability.

Conclusion

Multilayer packaging continues to be the primary method for the preservation and protection of the consumer goods, but its complex structure is the main obstacle to the sustainable waste

management. Even though the blend of materials that characterizes the packaging regarding barrier and mechanical properties also makes recycling difficult, still recycling is taking place and has huge environmental impact. The advent of chemical and solvent-based recycling methods, the application of compatibilization techniques, and the redesign of mono-materials are drastically altering the recycling and reusing process of multilayer packaging. The eco-friendly governmental policies and the global transition to circular economy models, indicates that the era of sustainable multilayer packaging is not going to be just a distant dream but something that can be realized in the near future. Future packaging sector will have to make collaboration among scientists, government, and producers its top priority in order to make the innovations fall in line with safety, performance, and environmental responsibility.

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AQUAPORINS AND DROUGHT TOLERENCE IN CEREALS

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Summary

Aquaporins are complex proteins present in plant system regulating water homeostatis and facilitating water movement. Thus genes related to crops like PIPs,TIPs and SIPs can be used markers in crops and varieties with better drought tolerance.

Introduction

Aquaporins are membrane intrinsic proteins (MIP) that form pores in the cellular membranes, which facilitate the movement of water and many other molecules such as ammonia, urea, CO_2, micronutrients (silicon and boron), glycerol and reactive oxygen species (hydrogen peroxide) across the cell and intercellular compartments.

Configurations

The MIP sequences take on a typical helical fold with six transmembrane helices and two half-helices. The stability of the functionally important half-helix is modulated by stabilising the intra-helical salt-bridge interaction and/or two helix-destabilising residues glycine and proline. From crystallography analyses configurations are given in Fig.1.

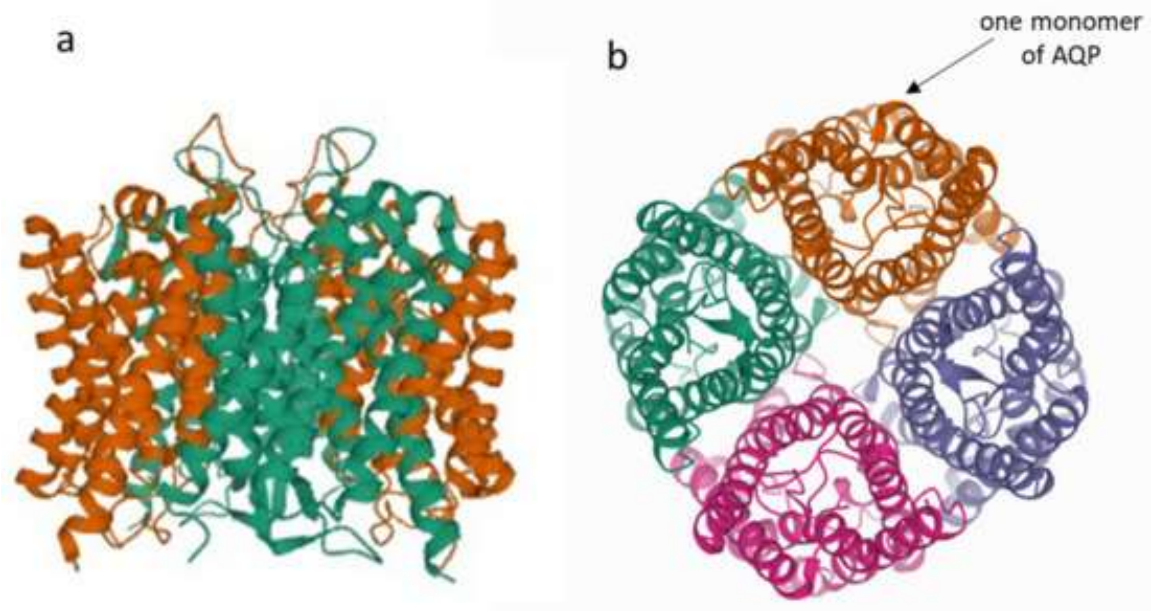


Fig.1.Configurations of AQPs in monomer(a) and tetramer(b) adopted from Kuroskwa ,2025.

Aquaporins (AQPs) are specialized membrane water channel proteins that regulate cellular water homeostasis, root hydraulic conductivity, and transpiration under drought stress in cereal crops

Mechanisms

AQPs are typically divided into five subfamilies: the plasma membrane intrinsic proteins (PIP), tonoplast intrinsic proteins (TIP), nodulin-26-like proteins (NIP), small, basic intrinsic proteins (SIP)

and the uncategorised X intrinsic proteins (XIP). However, in the monocot plant species, the XIP subfamily was lost during the evolution. The PIPs, NIPs and XIPs are mainly localized in the cytoplasmic plasma membrane, while the TIPs are localized in the tonoplast—a membrane of the vacuole. Total and indivisual AQPs of some cereals are given in Table 1 in the below. So far known Wheat (*Triticum aestivum* L.) has high number of AQPs. Cereals which can grow in less amount of water are usually having less number of AQPs.

Table1. Segregations of AQPs in some cereals (modified from Kruoskwa,2025)

Species	AQP	PIP	TIP	NIP	SIP
Bread wheat (*Triticum aestivum* L.)	113 (65-A, 42-B, 36-D)	51	29	29	4
Maize (*Zea mays* L.)	41	12	18	8	3
Rice Japonica (*Oryza sativa*)	33	11	10	10	2
Barley (*Hordeum vulgare* L.)	39	18	11	8	2
Sorghum (*Sorghum bicolor* (L.) *Moench*)	37	13	11	11	2
Foxtail millet (*Setaria italica*)	39	12	11	13	3
Pearl millet (*Pennisetum glaucum* (L.) R Br.)	33	10	9	11	3

In wheat, exploration of the molecular mechanisms underlying the proposed differentiation between isohydric and anishydric genotypes showed that the overexpression of the PIP2:1 gene and the absence of induction of AAO gene expression under water-stressed conditions represent potential indicators for preliminary selection, even at a very early stage, of drought-tolerant genotypes . In the resistant genotypes, PIP2:1 was significantly upregulated whereas in the sensitive ones, its expression showed only a slight induction (Guizani *et al*., 2023).

In drought-sensitive plant *Zea mays*, the expression of TIPs and PIPs genes is mainly concentrated in the roots and ears. In *Oryza sativa*, TIP genes are more involved in water absorption in the roots and regulation during seed development, while PIP genes show more prominent expression in the leaves and flowering stages

TIPs subfamily reveal significant functional divergence: TIP1 and TIP4 subclusters broadly engage in drought response across plant species, followed by TIP2 and TIP3 subclusters, whereas TIP5 subcluster shows negligible responsiveness, suggesting its functional specialization may be governed by subcluster-specific regulation. Compared to DT(Drought tolerant)) plants, DS (Drought sensitive) plants exhibit greater diversity in TIPs subclusters, with TIP1 subcluster consistently serving as the core drought-responsive module . Additionally, TIP4;1 subcluster in DS plants demonstrates distinct drought-responsive activity

PIP subfamily of DS plants, PIP1;2, PIP1;4, and PIP2;2 subclusters universally participate in drought response, followed by secondary responders including PIP1;3, PIP2;4, PIP2;5, PIP2;7, and PIP2;8 subclusters. Notably, maize (*Zea mays*) displays the highest number of drought-responsive genes in the PIP2;2 subcluster, predominantly showing upregulated expression, whereas in *Arabidopsis thaliana*, most drought-responsive PIP genes are downregulated (Li *et al*.,2025). It is believed that the differential expression of TIPs and PIPs genes across different tissues may work in coordination to participate in water metabolism and drought responses in plants.

Conclusion

Tolerant cereal genotypes (such as specific wheat and barley lines) often exhibit distinct upregulation of key AQP genes like *PIP2;1*.

Overexpression of specific aquaporin-encoding genes has been shown to improve antioxidant defense mechanisms, reduce leaf water loss, and sustain grain filling during drought.

Overexpressing specific aquaporin-encoding genes in transgenic cereals has been shown to improve membrane stability, enhance antioxidant enzyme activities, and maintain grain filling during severe water deficits.

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FISHERIES RESOURCE MANAGEMENT: PRINCIPLES AND PRACTICES

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Introduction

Fisheries resources are among the most important renewable natural resources supporting food security, employment, livelihoods and economic development worldwide. Fish and other aquatic organisms provide high-quality animal protein, essential micronutrients and income to millions of people, particularly in coastal and rural communities. However, fisheries resources are finite and are increasingly threatened by overfishing, habitat degradation, pollution, climate change, invasive species and illegal, unreported and unregulated fishing. Rapid development of coastal and inland areas has further increased pressure on aquatic ecosystems and fish populations. Fisheries resource management refers to the systematic planning, regulation, monitoring and conservation of aquatic living resources to ensure their sustainable utilization. It integrates biological, ecological, economic, social and institutional considerations for effective resource management. While traditional fisheries management mainly focused on maintaining fish stocks and controlling fishing mortality, modern approaches also emphasize ecosystem health, habitat conservation, climate resilience, precautionary management and stakeholder participation. The primary objective is not merely to maximize short-term fish production but to maintain fish populations at biologically sustainable levels while ensuring long-term benefits for present and future generations. Sustainable fisheries management therefore requires a balanced combination of scientific assessment, appropriate regulations, responsible fishing practices, habitat protection, continuous monitoring, community participation and effective governance.

Importance of fisheries resource management

Fisheries resource management is important because aquatic resources provide essential ecological, economic and social benefits to human societies. Fisheries contribute significantly to food and nutritional security by providing high-quality animal protein and essential micronutrients to populations worldwide. They also generate employment and income through harvesting, processing, transportation, marketing and other related activities, particularly supporting livelihoods in coastal and rural communities. From an ecological perspective, fish are important components of aquatic food webs and contribute to nutrient cycling, energy transfer and ecosystem functioning. Changes in fish abundance can influence predator–prey relationships and the structure and stability of aquatic ecosystems. Effective fisheries management also supports the conservation of aquatic biodiversity by protecting commercially important, threatened, endemic and ecologically significant species. Protection of spawning grounds, nursery areas, wetlands, mangroves, estuaries, rivers and lakes is therefore an important part of sustainable resource management. Fisheries management helps prevent resource depletion by maintaining fishing mortality at levels that allow fish populations to reproduce and replenish naturally. Management measures such as catch limits, closed seasons, minimum mesh sizes, closed areas and fishing-effort restrictions can help maintain

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fish stocks within sustainable limits. Sustainable management also promotes responsible fishing practices and reduces harmful impacts on non-target species and habitats. In addition, effective management can improve the resilience of fisheries to environmental changes, climate variability and other emerging pressures. Thus, fisheries resource management is essential for maintaining productive aquatic ecosystems while securing long-term ecological, economic and social benefits for present and future generations.

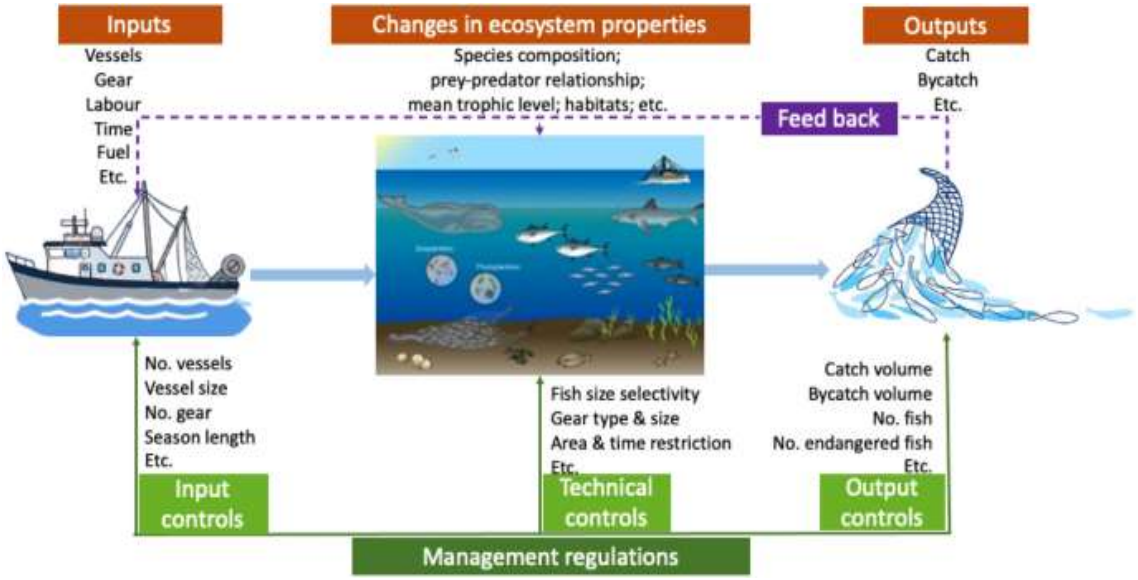


Figure 1. Importance of fisheries resource management

Principles of fisheries resource management

Sustainable utilization

Sustainable utilization is the fundamental principle of fisheries resource management and aims to harvest aquatic resources at levels that allow natural populations to reproduce and replenish. It requires consideration of recruitment, growth, natural mortality, fishing mortality and environmental variability. The maximum sustainable yield (MSY) has traditionally been used as a reference point for fisheries management, but modern approaches recognize that maximum production alone may not adequately protect biodiversity and ecosystem functioning. Therefore, management objectives should integrate biological sustainability with ecological, economic and social considerations.

Precautionary principle

The precautionary principle is important when scientific information about fish stocks or ecosystem conditions is incomplete or uncertain. The absence of complete scientific evidence should not delay conservation measures when there is a risk of serious or irreversible resource degradation. Precautionary management may include conservative catch limits, protection of spawning populations, restrictions on destructive fishing practices and establishment of closed areas. This approach helps reduce the risk of excessive exploitation and supports long-term resource conservation.

Ecosystem-based management

Ecosystem-based fisheries management recognizes that fish populations are closely connected with their surrounding ecosystems. Fish interact with prey, predators, competitors, habitats and

environmental conditions, and fishing activities can influence these relationships. Management therefore considers ecosystem structure and functioning along with the status of individual fish stocks. Important measures include habitat protection, bycatch reduction, conservation of non-target species and maintenance of food-web relationships. This approach is particularly important under climate change, as changes in temperature, rainfall, salinity and dissolved oxygen can influence fish distribution and productivity.

Conservation of biodiversity

Conservation of biodiversity is an important component of sustainable fisheries management. Management should maintain species diversity, genetic diversity and ecosystem diversity while protecting vulnerable species and breeding populations. Excessive or selective removal of particular species or size groups can alter population structure and potentially affect genetic characteristics. Protection of critical habitats, spawning grounds, nursery areas and threatened aquatic species is therefore necessary to maintain healthy and productive aquatic ecosystems.

Equity and social responsibility

Fisheries resources provide livelihoods and income to many communities, particularly where alternative employment opportunities are limited. Fisheries management should therefore consider the social and economic consequences of management measures for resource users. Equitable allocation of fishing opportunities, stakeholder participation and recognition of local and traditional knowledge can improve the acceptance and effectiveness of management interventions. Inclusive decision-making also helps address conflicts among different groups dependent on aquatic resources.

Adaptive management

Adaptive management recognizes that aquatic ecosystems are dynamic and that fisheries decisions are often made under uncertainty. It involves implementing management measures, monitoring their outcomes and modifying strategies when new information becomes available. Continuous assessment allows managers to respond to changes in fish stocks, environmental conditions, fishing practices and socioeconomic circumstances. This approach supports flexible and responsive fisheries governance under changing ecological and climatic conditions.

Assessment of fisheries resources

Scientific assessment provides the foundation for effective fisheries resource management by generating information on stock abundance, recruitment, growth, mortality, exploitation and population structure. Such information helps determine whether existing fishing pressure is sustainable and supports the development of appropriate management measures. Fisheries assessment commonly uses catch and effort data, length-frequency information, age composition, biological sampling and fishery-independent surveys. Catch-per-unit-effort (CPUE) can provide an index of relative abundance when fishing effort and catchability are appropriately standardized, while length-based methods are useful where reliable age data are unavailable. Population parameters such as growth rate, natural mortality, fishing mortality, recruitment and biomass are important indicators of stock condition, and age-structured or biomass-based models may be applied for detailed assessments. However, assessment accuracy depends strongly on the quality, quantity and representativeness of available data. In small-scale and inland fisheries, formal stock assessment can be challenging because catches are dispersed among numerous fishers and landing sites. In such situations, participatory monitoring, community-based data collection, landing surveys

and simplified assessment methods can provide useful information for supporting fisheries management decisions.

Fisheries management measures

Fisheries management measures are essential for controlling fishing pressure and maintaining fish stocks within sustainable limits. Catch regulation involves establishing total allowable catches or other catch limits to control the quantity of fish removed from a stock and is most effective when supported by reliable stock information, monitoring and enforcement. Fishing effort can be regulated by limiting the number of vessels, fishing days, fishing hours, gear units or engine capacity, particularly where direct catch monitoring is difficult. Minimum legal size regulations prevent the capture of immature individuals and allow fish to reproduce before harvest, thereby supporting recruitment and spawning stock biomass. Mesh-size regulations improve gear selectivity by allowing smaller fish to escape and are commonly applied to gillnets, trawls and other net-based gears. Closed seasons can protect mature fish during spawning periods and support successful recruitment, while closed areas, fish refuges and protected habitats provide safe areas for reproduction and growth. Gear restrictions can reduce juvenile mortality, bycatch and habitat damage through the prohibition of destructive gears or the use of modifications such as bycatch reduction devices and escape panels. The effectiveness of these measures depends on appropriate scientific information, stakeholder cooperation, regular monitoring and effective enforcement.

Habitat conservation and restoration

Healthy aquatic habitats are fundamental to sustainable fisheries because rivers, floodplains, lakes, reservoirs, wetlands, estuaries, mangroves, seagrass beds, coral reefs and coastal ecosystems provide feeding, breeding, nursery and shelter areas for aquatic organisms. Habitat degradation can reduce fish abundance even when fishing pressure is controlled, making habitat conservation an integral component of fisheries management. Important measures include pollution control, maintenance of environmental flows, wetland protection, conservation of riparian vegetation, reduction of excessive sedimentation and restoration of degraded habitats. In coastal areas, conservation and restoration of mangroves and estuaries are particularly important because they provide nursery habitats for many fish and shellfish species. In inland waters, maintaining river connectivity is essential because dams and other barriers can interrupt fish migration, spawning and recruitment. Where appropriate, ecological connectivity and fish passage facilities can help maintain migratory fish populations and improve the ecological functioning of aquatic systems.

Community-based fisheries management

Community-based fisheries management recognizes the important role of local communities in the use and conservation of aquatic resources. Involving fishers and other stakeholders in decision-making, monitoring and enforcement can improve compliance, local ownership and resource stewardship. Local fishers possess valuable knowledge regarding fishing grounds, seasonal fish movements, spawning periods, catch composition and environmental changes, which can complement scientific information. Co-management further strengthens this approach by sharing management responsibilities among government agencies, fishing communities, researchers and other stakeholders. Successful community-based management requires clearly defined responsibilities, transparent decision-making, effective communication, institutional support and mechanisms for resolving conflicts. Participation of resource users can therefore contribute to management systems that are more locally appropriate and socially acceptable.

Monitoring, control and surveillance

Monitoring, control and surveillance (MCS) are essential for ensuring compliance with fisheries regulations and supporting effective resource management. Monitoring activities may include collection of catch and effort data, vessel registration, landing-site surveys and electronic reporting. Modern technologies such as vessel monitoring systems, automatic identification systems, remote sensing, satellite imagery, electronic logbooks, drones and geographic information systems can strengthen surveillance and assist in detecting fishing activities and potential violations. Illegal, unreported and unregulated (IUU) fishing remains a major challenge because it can undermine legitimate fisheries, reduce fish stocks and weaken management measures. Effective licensing, traceability, port controls, surveillance and enforcement are therefore important for preventing IUU fishing and improving compliance with fisheries regulations.

Digital technologies in fisheries management

Digital technologies are increasingly supporting fisheries assessment, monitoring and decision-making. Remote sensing provides information on sea surface temperature, chlorophyll concentration, ocean colour, water bodies and habitat characteristics, while geographic information systems facilitate the integration and analysis of spatial fisheries information. Artificial intelligence and machine learning can assist with fish identification, catch estimation, stock assessment, vessel activity detection and analysis of large datasets. Underwater cameras and automated image-recognition systems can improve monitoring of fish populations and aquatic biodiversity. Mobile applications can also provide fishers with weather information, market prices, disease alerts, fishing advisories and management notifications. However, digital technologies should complement rather than replace field-based monitoring, scientific surveys and stakeholder participation.

Climate change and fisheries resource management

Climate change is increasingly affecting fisheries through changes in temperature, precipitation, ocean circulation, sea-level rise, extreme weather events, oxygen availability and habitat distribution. These changes can influence fish distribution, migration, growth, reproduction and productivity. Climate-resilient fisheries management therefore requires flexible and adaptive strategies based on continuous monitoring of environmental conditions and fish populations. Management measures may need to be adjusted as species composition, productivity and resource distribution change. Protection and restoration of climate-sensitive habitats can strengthen ecosystem resilience, while diversification of livelihoods can reduce dependence on individual fisheries resources and help vulnerable fishing communities cope with climate-related changes.

Responsible fishing practices

Responsible fishing aims to minimize unnecessary mortality, habitat damage, bycatch and other ecological impacts while maintaining the benefits obtained from fisheries. Selective fishing gears, appropriate mesh sizes, reduced discards and effective bycatch management are important components of responsible fishing. Improved post-harvest handling through proper icing, hygienic handling, storage, transportation and processing can reduce losses and increase the value obtained from existing catches without increasing fishing pressure. Fishers should also be encouraged to release protected or unwanted species whenever survival is possible and avoid fishing in ecologically sensitive habitats. Awareness programmes, training and extension services are important for promoting responsible fishing practices and improving compliance with conservation measures.

Fisheries governance and institutional framework

Effective fisheries management requires appropriate legislation, policies, institutions and enforcement mechanisms involving government departments, research organizations, fishing communities, private-sector organizations, non-governmental organizations and other stakeholders. Clearly defined institutional responsibilities can reduce duplication, management gaps and conflicts, while fisheries policies should be based on scientific evidence and periodically reviewed according to changes in resource status and environmental conditions. International cooperation is particularly important for shared, transboundary and migratory fish stocks. Regional fisheries management organizations and international agreements provide mechanisms for coordinating management actions among countries that share aquatic resources. Strong governance is therefore essential for translating scientific recommendations and management policies into effective conservation and sustainable resource use.

Sustainable fisheries management in India

India possesses diverse fisheries resources across marine, coastal and inland ecosystems, including rivers, reservoirs, wetlands, lakes, estuaries and coastal waters that support a wide range of fish and shellfish species. Fisheries and aquaculture contribute substantially to employment, nutrition and income, making sustainable resource management important for both ecological and socioeconomic well-being. Indian fisheries management requires an integrated combination of resource conservation, sustainable harvesting, aquaculture development, habitat protection and community participation. Inland fisheries management needs to address overfishing, habitat degradation, pollution, invasive species and loss of river connectivity, while marine fisheries management requires attention to fishing capacity, bycatch, habitat impacts, seasonal restrictions and conservation of vulnerable species. Development of fisheries infrastructure, digital monitoring, fisher training, cold-chain facilities and value addition can further support sustainable fisheries. Collaboration among fisheries departments, universities, research institutions and fishing communities is also essential for improving scientific assessment and management practices.

Conclusion

Fisheries resource management is a multidisciplinary process that seeks to balance the utilization and conservation of aquatic living resources. Sustainable fisheries require reliable scientific information, appropriate regulations, habitat conservation, responsible fishing practices, effective monitoring, strong governance and meaningful stakeholder participation. Modern management increasingly combines traditional catch and effort controls with precautionary, ecosystem-based, adaptive and participatory approaches. Long-term sustainability depends not only on controlling fishing pressure but also on maintaining healthy aquatic ecosystems through protection and restoration of spawning and nursery habitats, pollution reduction, biodiversity conservation and control of destructive fishing practices. Digital technologies provide new opportunities for improving assessment, monitoring and enforcement, while community participation provides an important foundation for successful implementation. An integrated approach combining science, technology, local knowledge, effective governance and stakeholder cooperation can help maintain productive, resilient and sustainable fisheries while ensuring continued food, livelihood, economic and ecological benefits for present and future generations.

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CONVERTING UNUSABLE BIOMASS INTO QUALITY PLANTING MATERIAL IN *Valeriana jatamansi*

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Abstract

Conventional propagation of endangered medicinal plants often relies on destructive harvesting of economically valuable underground organs or costly tissue culture systems, creating a fundamental conflict between species conservation and commercial utilization. We hypothesized that the medicinally unusable aerial stem nodes of *Valeriana jatamansi* possess sufficient regenerative competence to generate high-quality planting material (QPM), thereby enabling non-destructive, low-cost, and sustainable clonal propagation. To test this hypothesis, aerial stem node cuttings were evaluated under a simple soilless growth system without plant growth regulators, aseptic culture, or tissue culture infrastructure. The protocol achieved 100% plant emergence and more than 91 ± 5.56% field survival without a hardening phase, demonstrating exceptional regenerative capacity and field adaptability. Regenerated plants exhibited robust vegetative growth and subsequently produced additional aerial nodes, enabling continuous and exponential clonal multiplication. Importantly, this strategy completely avoids sacrificing the medicinally valuable rhizome and adventitious roots, which are the primary sources of valerenic acid and valepotriates. Unlike conventional hormone-supplemented MS-based micropropagation, the proposed approach requires neither sophisticated laboratory facilities nor specialized technical expertise, making it readily adoptable at the farmer and nursery levels. This study establishes, for the first time, a regenerative propagation framework that converts previously discarded aerial biomass into a renewable source of quality planting material. Beyond introducing a practical propagation technology, the work provides a sustainable conservation strategy that simultaneously preserves medicinal biomass, reduces harvesting pressure on wild populations, and supports large-scale restoration and commercial cultivation of the highly endangered Himalayan medicinal plant *Valeriana jatamansi*.

Keywords: *Valeriana jatamansi*; Quality planting material; Sustainable clonal propagation; Conservation biotechnology; Non-destructive propagation

Highlights

(i) Transforms discarded aerial biomass into renewable quality planting material.
(ii) Decouples unusable medicinal biomass for clonal propagation for the first time.
(iii) Aerial stem nodes achieved 100% regeneration without MS medium or plant hormones.
(iv) More than 91% of regenerated plants survived field establishment without hardening.

(v) Introduces a non-MS, non-sterile propagation platform for endangered medicinal plants.
(vi) Establishes a self-renewing clonal multiplication system from aerial stem nodes.
(vii) Provides a scalable conservation technology for sustainable cultivation of *V. jatamansi*.

Key messages

♦ Medicinally unusable aerial stem nodes of Valeriana jatamansi possess remarkable regenerative competence and can be converted into renewable quality planting material.

♦ The study introduces a non-MS, non-sterile, hormone-free clonal propagation platform that eliminates the need for conventional tissue culture infrastructure.

♦ Direct regeneration from aerial stem cuttings achieved complete plant emergence and high field survival without a hardening phase, demonstrating practical field applicability.

♦ By utilizing discarded aerial biomass instead of rhizomes, the propagation system preserves the economically valuable medicinal organs while simultaneously producing new planting material.

♦ Regenerated plants continuously produce new aerial nodes, creating a self-renewing and potentially exponential clonal multiplication system for sustainable cultivation.

♦ The work establishes a new conservation paradigm that decouples medicinal biomass production from plant propagation, reducing harvesting pressure on endangered natural populations.

♦ This low-cost, farmer-friendly technology provides a scalable strategy for commercial cultivation, germplasm conservation, and ecological restoration of *Valeriana jatamansi*, with potential applicability to other medicinal plants propagated through destructive harvesting.

Introduction

Valeriana jatamansi Jones (Valerianaceae) is a highly endangered medicinal plant naturally distributed in the North-Eastern Himalayan region at elevations ranging from 1000 to 3000 m above sea level (Bhattacharjee, 2000). The species typically inhabits hill slopes, moist forests, damp woodlands, ditches, and stream banks, where it has long been harvested for its medicinal properties. However, indiscriminate and destructive collection from natural habitats has severely depleted wild populations, resulting in its recognition as a highly endangered medicinal plant (Sher et al., 2011). Consequently, developing an efficient propagation strategy that simultaneously supports species conservation and sustainable commercial cultivation has become an urgent priority.

Conventional propagation methods suffer from several inherent limitations. Although seed propagation represents the natural reproductive pathway, *V. jatamansi* exhibits poor seed germination and rapidly declining seed viability, making large-scale multiplication unreliable (Kaur et al., 1999). Under our experimental conditions, freshly harvested seeds exhibited only 13.02 ± 1.08% germination, which declined to 7.26 ± 2.74% after one month of storage at room temperature, while six-month-old seeds completely lost their germination capacity. Furthermore, seed-derived progenies do not maintain the genetic uniformity of elite parental genotypes, limiting their suitability for commercial production of uniform medicinal crops.

Vegetative propagation through rhizomes has been considered an alternative approach because it preserves the parental genotype. However, this strategy creates a fundamental conflict between propagation and medicinal yield. The rhizome and adventitious roots constitute the principal economic organs of *V. jatamansi*, serving as the primary source of pharmacologically important compounds, including valerenic acid and valepotriates, which are extensively utilized in traditional

medicine for the treatment of obesity, skin disorders, epilepsy, insanity, and snake poisoning (Prakash, 1999; Mishra, 2004). Consequently, using rhizomes as propagules directly sacrifices the most valuable medicinal biomass, reducing harvestable yield while simultaneously limiting propagation efficiency.

Plant tissue culture has been developed to overcome some of these constraints, but its large-scale adoption remains restricted by high production costs and dependence on specialized laboratory infrastructure. Successful micropropagation requires aseptic culture conditions, hormone-supplemented Murashige and Skoog (MS) medium, autoclaving and sterilization facilities, laminar airflow cabinets, controlled growth rooms, skilled personnel, high-quality water, and post-culture hardening before field establishment. These requirements substantially increase production costs and reduce accessibility for commercial nurseries and resource-limited farmers.

Despite considerable advances in propagation technologies, an important biological question has remained unexplored: Can medicinally unusable aerial plant parts be converted into renewable quality planting material without sacrificing the economically valuable underground organs? Addressing this question would fundamentally separate medicinal biomass production from propagation, thereby enabling simultaneous conservation of endangered germplasm and sustainable cultivation.

We hypothesized that the aerial stem nodes of *V. jatamansi*, although traditionally regarded as medicinally unusable biomass, possess sufficient regenerative competence to generate genetically uniform quality planting material through vegetative regeneration. Such an approach would preserve the medicinally important rhizome and adventitious roots, eliminate dependence on costly tissue culture systems, and establish a continuous, farmer-friendly propagation platform capable of exponential clonal multiplication.

To test this hypothesis, aerial stem cuttings (7.45 ± 0.32 cm) collected from mother plants were cultured in an artificial soilless substrate under controlled environmental conditions (8000 LUX light intensity, 14 h photoperiod, and 70% relative humidity) to evaluate their capacity for direct plant regeneration. Because each regenerated plant subsequently produces multiple aerial nodes that can serve as propagules in the following propagation cycle, this strategy has the potential to generate continuous and exponential production of quality planting material while preserving the economically valuable rhizome and root system. Thus, the present study introduces a regenerative propagation framework that transforms previously discarded aerial biomass into a renewable source of true-to-type planting material, providing a simple, low-cost, and scalable strategy for conservation, commercial cultivation, and long-term restoration of the endangered medicinal plant *Valeriana jatamansi*.

Materials and Methods

The study was conducted over three consecutive years (2016–2018) in the Terai region of West Bengal, India (28°19’N, 89°23’E; 43 m above mean sea level), to evaluate the repeatability and robustness of aerial stem node-mediated propagation in *Valeriana jatamansi* (Jones) (Valerianaceae), an endangered Himalayan medicinal plant naturally distributed between 1000 and 3000 m above sea level. Healthy mother plants were used as the source of aerial stem cuttings because conventional propagation generally requires sacrificing the economically valuable rhizome and adventitious roots. Stem cuttings (7.45 ± 0.32 cm) containing aerial nodes were planted in a

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soilless artificial substrate composed of perlite, peat moss, and vermiculite. Perlite improved aeration and root development, peat moss enhanced moisture retention and gradual nutrient availability, whereas vermiculite improved soil porosity and water–nutrient exchange, collectively providing a favorable environment for rapid plant emergence and early growth. To maintain high humidity during the regeneration phase, pots containing the artificial substrate were placed inside transparent plastic boxes with lids and maintained under controlled environmental conditions of 8000 LUX light intensity, a 14-h photoperiod, and 70% relative humidity for at least 14 days to ensure successful plant emergence.

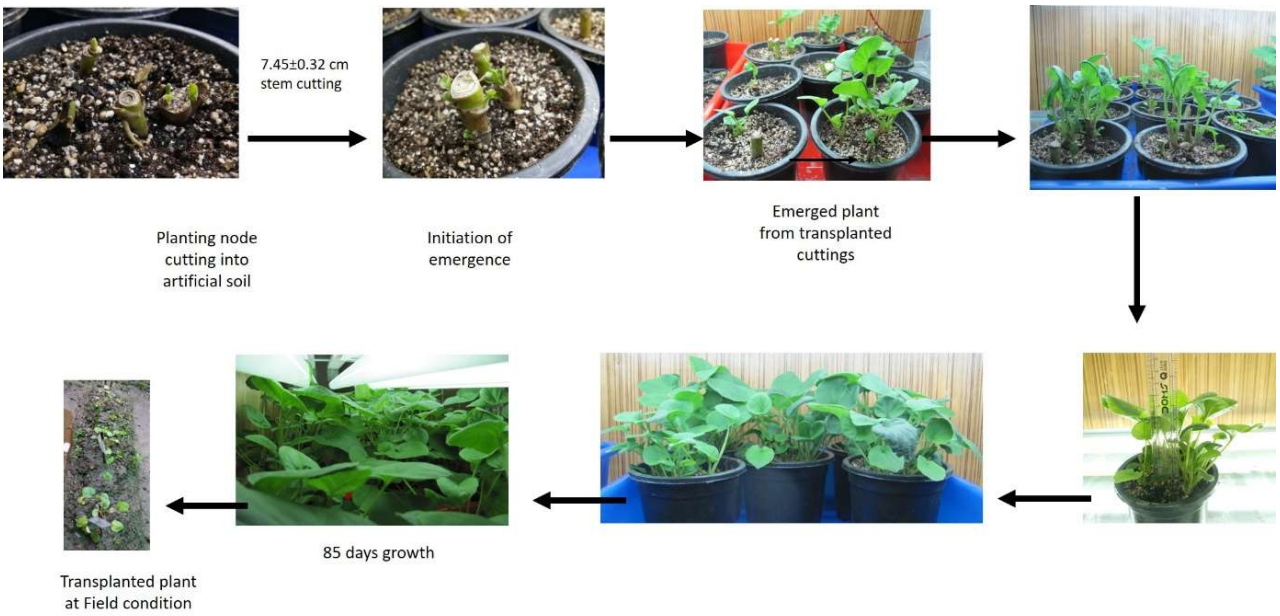


Fig. 1. Bird's-eye view of a simple, non-sterile plant regeneration system from aerial nodal cuttings established directly in artificial soil under controlled Plant Growth Room conditions (3000 LUX light intensity, 14 h photoperiod, and 70% relative humidity). The same nodal explant has previously been used as an explant for conventional in vitro tissue culture. However, the present study demonstrates, for the first time, that identical aerial nodal cuttings can regenerate directly in an artificial soil substrate without Murashige and Skoog (MS) medium or aseptic tissue culture conditions. This approach represents a practical alternative to conventional micropropagation by eliminating the requirement for costly tissue culture infrastructure, including contamination-free laboratories, autoclaving facilities, laminar airflow cabinets, repeated explant sterilization, high-purity water, specialized hardening units, and continuous supervision by trained personnel. Consequently, this non-MS-based propagation strategy provides a low-cost, scalable, and farmer-friendly platform for rapid multiplication of planting materials, particularly for medicinal and high-value plant species where conventional tissue culture is economically or technically restrictive.

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Fig. 2. Clonal Propagation through Aerial Stem Cuttings under Plant Growth Room Conditions

Result

The present study demonstrates, for the first time, that the medicinally unusable aerial stem nodes of the endangered medicinal plant *Valeriana jatamansi* possess sufficient regenerative competence to serve as a renewable source of quality planting material (QPM), thereby providing a non-destructive alternative to conventional rhizome-based propagation. Unlike the rhizome and adventitious roots, which constitute the economically valuable medicinal organs containing valerenic acid and valepotriates and are harvested for the treatment of obesity, skin diseases, epilepsy, insanity, and snake poisoning, the aerial stem and leaves have no recognized medicinal or Ayurvedic utilization (Fig. 1). Exploiting these otherwise discarded aerial nodes for propagation therefore preserves the medicinal yield while simultaneously generating new planting material. Under controlled environmental conditions (8000 LUX light intensity, 14-h photoperiod, and 70% relative humidity), aerial stem cuttings (7.46 ± 0.32 cm) consistently regenerated new plants over three consecutive years (2016–2018), confirming the robustness and repeatability of the propagation strategy. Each cutting produced an average of 2.71 ± 0.397 regenerated plants within 85 days, corresponding to 0.61 ± 0.16 sub-plants per original node. The regenerated plants attained a total length of 31.85 ± 1.47 cm, including a root system measuring 13.34 ± 0.81 cm, accumulated a fresh biomass of 23.09 ± 4.14 g, developed an additional 7.0 ± 1.27 aerial nodes, and produced 17.04 ± 0.04 leaves during the growth period (Fig. 1). Importantly, the formation of multiple new aerial nodes on regenerated plants establishes a self-renewing propagation cycle in which each

generation provides additional propagules for subsequent multiplication. This regenerative strategy enables continuous and exponential production of genetically uniform quality planting material without sacrificing the economically valuable underground organs or relying on hormone-supplemented MS-based tissue culture, thereby offering a practical conservation and commercial propagation platform for the endangered species *V. jatamansi*.

Discussion

Valeriana jatamansi (Jones) (Valerianaceae) is a highly endangered Himalayan medicinal plant naturally distributed at elevations of 1000–3000 m above sea level (Bhattacharjee, 2000). Continuous overexploitation through destructive harvesting of underground organs has severely reduced natural populations, creating an urgent need for propagation strategies that simultaneously support biodiversity conservation and sustainable commercial cultivation. Although increasing demand from traditional and modern medicinal industries necessitates large-scale production of quality planting material (QPM) (Ved and Goraya, 2008), currently available propagation approaches either suffer from poor propagation efficiency or compromise medicinal yield. Seed propagation is constrained by low germination and rapid loss of viability, whereas rhizome-based propagation consumes the economically valuable medicinal organs that constitute the principal harvestable biomass. The present study addresses this long-standing conservation–utilization conflict by demonstrating, for the first time, that medicinally unusable aerial stem nodes can be converted into renewable quality planting material without sacrificing the rhizome and adventitious roots.

The major conceptual advance of this work lies not merely in establishing another vegetative propagation method but in redefining the biological role of aerial biomass in *V. jatamansi*. Traditionally, leaves and aerial stem nodes have little or no medicinal value and are generally discarded after harvest, while the rhizome and roots remain the exclusive targets for medicinal utilization. Our results demonstrate that these previously neglected aerial stem nodes possess remarkable regenerative competence, enabling them to function as propagules for producing genetically uniform planting material. Consequently, the medicinally valuable underground organs are completely preserved for phytochemical extraction, while the otherwise unusable aerial biomass is transformed into a renewable biological resource for species multiplication. This approach effectively decouples propagation from medicinal biomass production and establishes a sustainable strategy in which conservation and commercial utilization are achieved simultaneously rather than competitively.

Several studies have successfully developed tissue culture-based protocols for quality planting material production in *V. jatamansi* through hormone-mediated shoot organogenesis using Murashige and Skoog (MS) medium (Das et al., 2013; Chen et al., 2014). These protocols have demonstrated high multiplication efficiency under controlled laboratory conditions but require sophisticated infrastructure, including aseptic culture facilities, laminar airflow cabinets, autoclaves, controlled growth rooms, high-quality water, skilled technical personnel, and subsequent hardening before field establishment. Such requirements substantially increase production costs and limit adoption outside specialized laboratories. In contrast, the present study demonstrates that direct regeneration from aerial stem nodes can be achieved in a simple artificial soilless substrate under controlled environmental conditions without plant growth regulators, sterile culture, or tissue culture facilities. The elimination of these technical constraints substantially improves the practical feasibility of large-scale propagation, particularly for commercial nurseries, conservation programs, and resource-limited farming communities.

An additional advantage of the proposed propagation strategy is its self-renewing multiplication potential. Each regenerated plant develops multiple new aerial nodes that can subsequently serve as propagules for the next propagation cycle, thereby creating a continuous and exponential multiplication system without further exploitation of wild populations. Unlike rhizome propagation, where every new propagule reduces the available medicinal yield, aerial node propagation preserves the complete underground biomass while simultaneously generating additional planting material. This regenerative cycle offers a practical mechanism for reducing harvesting pressure on natural populations, facilitating ex situ conservation, and supporting sustainable cultivation to meet the growing industrial demand for *V. jatamansi*.

Overall, this study introduces a new regenerative propagation paradigm in which medicinally unusable aerial biomass is converted into renewable quality planting material while preserving economically valuable underground organs. Beyond providing a low-cost alternative to conventional tissue culture, the approach establishes a conservation-oriented production system that integrates clonal fidelity, sustainable utilization, and exponential multiplication into a single propagation framework. The concept of converting previously discarded plant biomass into planting material may also be applicable to other endangered medicinal species whose conventional propagation depends on destructive harvesting of economically important organs, thereby opening a new avenue for sustainable medicinal plant conservation and commercial production.

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Compliance with ethical standards (e.g. Conflict of interest)
The communicating author (HAM) declared that there is no conflict of interest.

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GHOST FISHING: THE FISHING THAT CONTINUES AFTER THE FISHER LEAVES

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Abstract
Fishing is an important source of food, employment and income for millions of people, but fishing activities can also create an unusual form of marine pollution known as ghost fishing. Ghost fishing occurs when lost, abandoned or discarded fishing gear continues to catch and kill marine organisms even though no fisher is operating it. Nets, traps, pots, hooks and lines can remain active underwater and may capture fish, crabs, turtles, seabirds and marine mammals. The problem is particularly concerning because many modern fishing gears are made from durable synthetic materials that can persist in the environment for long periods. Ghost gear can also damage habitats, contribute to marine debris and create economic losses for fisheries. This article discusses how ghost fishing occurs, its impacts on aquatic ecosystems and fisheries, and the measures that can help prevent and reduce this hidden form of fishing mortality.

Keywords: Abandoned fishing gear, marine pollution, marine biodiversity, ALDFG

Introduction

Imagine a fishing net lying silently on the seabed with no boat nearby and no fisher tending it. Although the fisher has left, the net may continue to trap animals. This phenomenon is known as ghost fishing. The broader term abandoned, lost or otherwise discarded fishing gear (ALDFG) refers to fishing equipment that has been left behind, lost or discarded in aquatic environments. Such gear can continue to capture target species as well as non-target and protected animals. Gillnets, traps and pots are particularly associated with ghost fishing, while lines and other gear can cause entanglement and habitat damage (Macfadyen *et al*., 2009). Fishing gear can be lost for several reasons, including storms, strong currents, gear becoming snagged on underwater structures, interactions with other fishing vessels and difficulties in retrieving damaged equipment. A global review found that interactions with other vessels and gear, marine weather and snagging on submerged features are important causes of gear loss (Richardson *et al.,* 2023).

Becomes a "Ghost When Fishing Gear"

Ghost fishing begins when fishing gear becomes separated from the fisher. A lost gillnet may continue to entangle fish as currents move it through the water, while a lost trap or pot may continue attracting animals with bait or trapped organisms. Once an animal becomes trapped, it may die from starvation, injury, predation or other causes. In some cases, the dead animal can attract additional scavengers, creating a cycle in which more organisms become trapped. The intensity of ghost fishing can change over time as gear becomes damaged, buried or covered by organisms and sediments (Matsuoka *et al*., 2005). The problem is particularly important because fishing gear is designed to catch animals efficiently. When the gear is lost, this catching ability does not necessarily disappear. Instead, the gear can become an uncontrolled fishing device operating

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without human supervision. This makes ghost fishing different from many other forms of marine litter.



Figure 1. GHOST GEAR CYCLE

A Hidden Threat to Fish and Marine Wildlife

Ghost gear can affect both commercially valuable species and animals that were never intended to be caught. Fish, crabs, lobsters, turtles, seabirds and marine mammals may become trapped or entangled. The resulting mortality can contribute to biodiversity loss and reduce the number of animals available to fisheries. ALDFG can also damage seabed habitats and interfere with active fishing gear and navigation (Macfadyen *et al*., 2009; Richardson *et al*., 2022). The problem is not limited to animal mortality. Synthetic fishing materials can persist in aquatic environments and contribute to plastic pollution. Lost gear can also transport organisms to new areas and may become associated with microplastic and other pollution pathways. Reviews of ghost gear have identified impacts ranging from wildlife entanglement and habitat degradation to broader effects on ecosystem services (Do & Armstrong, 2023). The scale of the problem is difficult to measure because much of the lost gear remains underwater and is therefore difficult to locate. A global study published in *Science Advances* highlighted the need for better quantitative estimates of fishing gear lost to the ocean (Richardson *et al.,* 2022).

From Ghost Gear to Solutions

Preventing ghost fishing requires action before, during and after gear loss. Better gear marking can help identify ownership and make lost equipment easier to locate. Fishers can also be encouraged to report lost gear and recover it whenever conditions allow. Collection facilities at ports can make responsible disposal easier, while targeted retrieval programmes can remove existing ghost gear

from the environment. Research is also exploring modifications to fishing gear that allow trapped animals to escape when gear is lost. Improved gear designs, biodegradable components, better monitoring and stronger waste-management systems can all contribute to reducing ghost fishing. Reviews have emphasized that prevention is particularly important because removing lost gear after it enters the environment can be difficult and expensive (Huntington, 2019; Richardson *et al.,* 2022). Awareness among fishing communities is equally important. Understanding why gear is lost and developing practical solutions with fishers can help reduce the amount of gear entering the marine environment. Recent research has highlighted sustainable fishing practices, policy interventions and awareness-building as important components of ghost-fishing mitigation.

Conclusion

Ghost fishing is a hidden form of fishing that continues even after the fisher has left. Lost nets, traps, lines and other fishing equipment can remain in the water and continue catching animals, damaging habitats and contributing to marine pollution. Because fishing gear is specifically designed to capture aquatic organisms, its environmental impact does not necessarily end when it is lost. Reducing ghost fishing requires a combination of responsible fishing practices, improved gear design, gear marking, reporting and recovery systems, proper disposal facilities, fisher participation and effective management. Preventing fishing gear from becoming "ghost gear" is not only a conservation measure but also a way to protect fish stocks, fishing livelihoods and healthier aquatic ecosystems.

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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

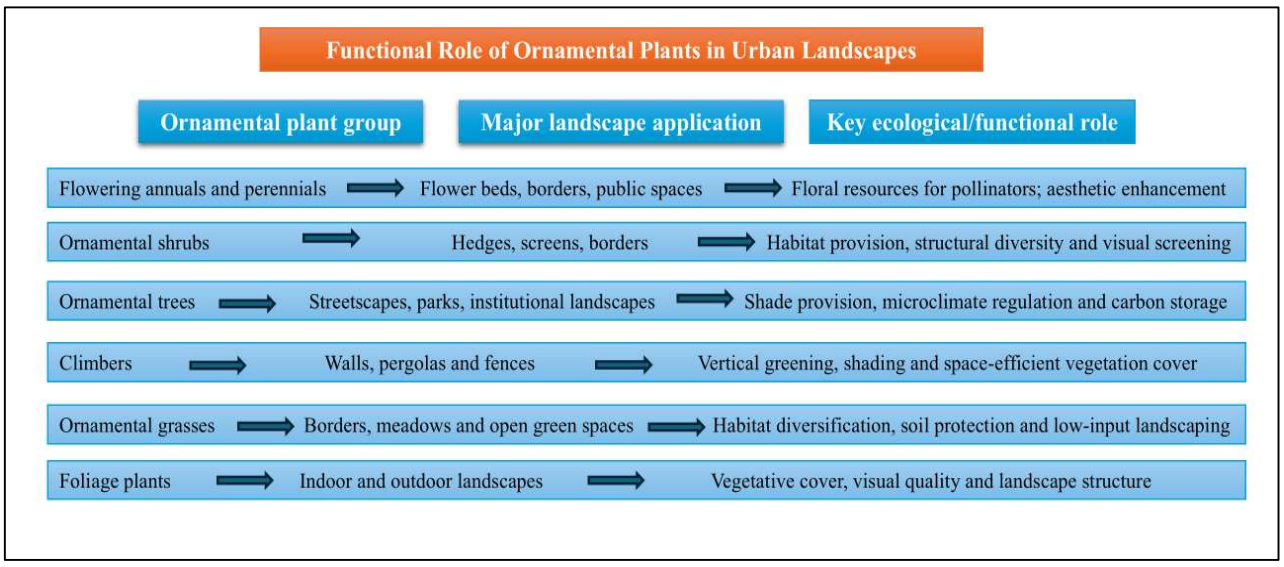
Urban floriculture is evolving from a primarily aesthetic activity into an important component of urban ecological management. Vegetated spaces can help moderate local microclimatic conditions, improve the visual and ecological quality of built environments and provide habitat and foraging resources 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.



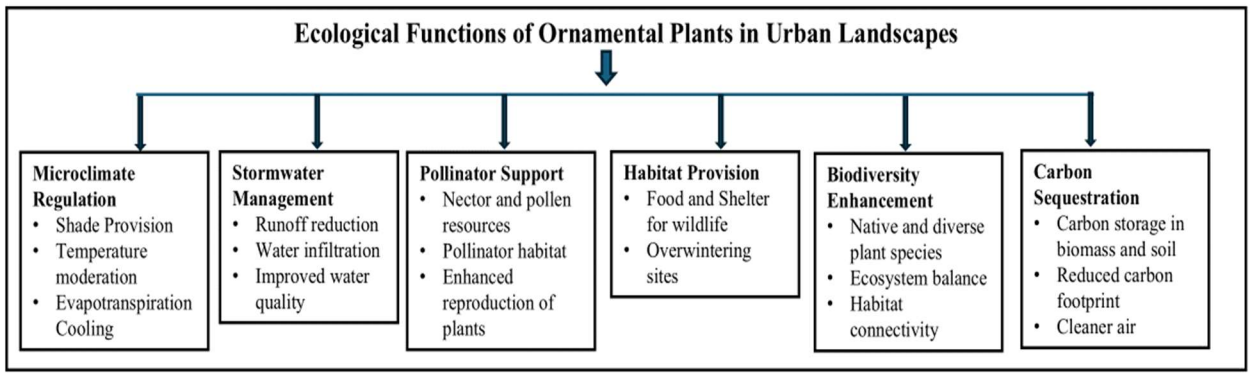
Landscape Plants as Urban Green Infrastructure

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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FISH GUT MICROBIOME IN AQUACULTURE: LINKING NUTRITION, GROWTH, IMMUNITY AND DISEASE RESISTANCE

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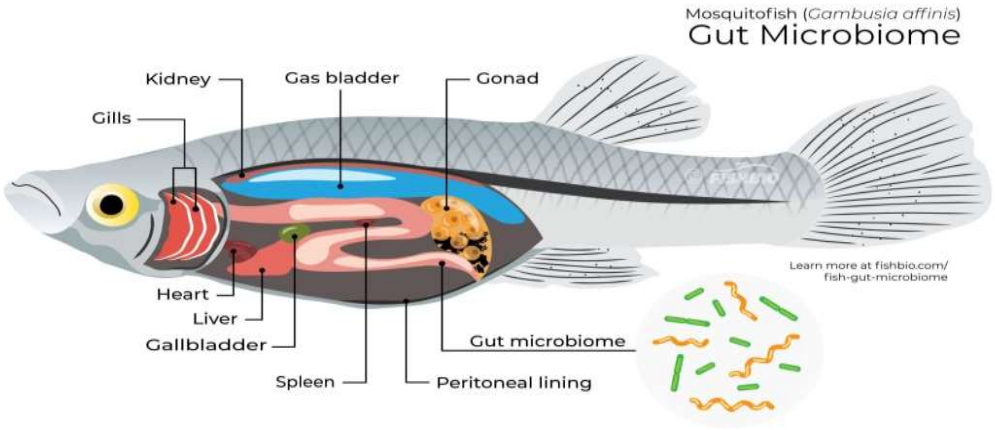
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Introduction

Aquaculture has become an important contributor to global food production, but increasing intensification has also created challenges related to disease, environmental stress and efficient feed utilization. Maintaining fish health without excessive dependence on antimicrobial treatments is therefore an important goal of sustainable aquaculture. The gastrointestinal tract is more than a digestive organ. It is a complex biological interface containing diverse microorganisms, collectively referred to as the gut microbiome. These microorganisms interact with the host and can influence nutrient utilization, intestinal barrier function, metabolism, immune responses and resistance to pathogens. Recent research has consequently shifted from simply identifying intestinal bacteria towards understanding their functions and their interactions with the fish host (Khmelevtsova *et al*., 2026)

Understanding the Fish Gut Microbiome

The fish gut microbiome is composed mainly of bacteria, together with other microorganisms. Its composition is influenced by several factors, including fish species, age, diet, genetics, temperature, water quality, environmental conditions and stress. Consequently, there is no single microbial community that can be considered “ideal” for every cultured fish. Research on commercially important species such as Nile tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchusmykiss*), and other aquaculture species shows that microbial communities can change in response to diet and farming conditions.



Source: FISHBIO, “Bugs and Guts: How the Gut Microbiome Helps Fish and Human Hosts, 2024

Gut Microbiome and Nutrition

One of the important functions associated with the gut microbiome is its contribution to digestion and nutrient utilization. Intestinal microorganisms can produce or influence enzymes and metabolites involved in the breakdown and utilization of dietary components. Microbial activity may therefore affect the availability of nutrients and feed efficiency. This relationship is particularly relevant when developing functional feeds. Probiotics, prebiotics and other dietary additives can modify the intestinal microbial community and, in turn, influence digestive and physiological processes. Reviews of aquaculture probiotics report effects involving digestive enzyme activity, antioxidant defence and other indicators of fish health, although responses vary between species and microbial strains (Amenyogbe *et al*., 2024; Hoseini *et al*., 2026). A recent example comes from Nile tilapia (*Oreochromisniloticus*). A 2026 study investigated fermented sesame oilcake as a functional dietary ingredient and found changes in gut microbial composition together with improved immune and antioxidant responses. . This example is important because it demonstrates that microbiome-related dietary interventions may affect health-related functions without necessarily producing a measurable increase in growth (Hoseini *et al*., 2026).

Gut Microbiome and Fish Growth

Growth depends on efficient digestion, nutrient absorption, metabolism and overall physiological health. Since the gut microbiome participates in these processes, researchers are investigating whether targeted microbial modulation can improve aquaculture performance. Pacific white-leg shrimp (*Penaeus vannamei*) provides a recent example. A 2026 study evaluated single- and multi-strain lactic acid bacterial probiotics in juvenile shrimp. Dietary supplementation with *Pediococcus pentosaceus* and *Lactiplantibacillus plantarum*improved growth performance compared with the control, while probiotic treatments also produced changes in gut histology and microbial community composition (Lalitha *et al*., 2026).

Gut Microbiome and Immunity

The intestine is an important immune interface because it is continuously exposed to food components, microorganisms and environmental substances. Interactions between intestinal microorganisms and the host can influence mucosal barrier function and immune signalling. Gut microorganisms may contribute to host defence through several mechanisms, including competition with pathogens, production of antimicrobial compounds and modulation of immune pathways. Recent reviews describe links between the gut microbiome and cytokine regulation, mucosal immune responses and antimicrobial defence (Khmelevtsova *et al*., 2026; Jiang *et al*., 2026). In aquaculture, this relationship has practical importance because improving intestinal health may help fish tolerate environmental stress and respond more effectively to infectious challenges.

Gut Microbiome and Disease Resistance

Disease outbreaks remain one of the major constraints on intensive aquaculture. The gut microbiome may contribute to disease resistance through competitive exclusion, antimicrobial activity, maintenance of intestinal barrier function and stimulation of host immunity. For example, research in rainbow trout (*Oncorhynchus mykiss*) has examined probiotic interventions in relation to intestinal microbiota, immunity and resistance to bacterial pathogens. Such studies indicate that changes in microbial communities can occur together with changes in immune responses and disease-related outcomes (Jiang *et al*., 2026). Current approaches include prebiotics, synbiotics, postbiotics, functional feeds and microbiome engineering, with the aim of producing more predictable effects on host health (Jiang *et al*., 2026; Khmelevtsova *et al*., 2026).

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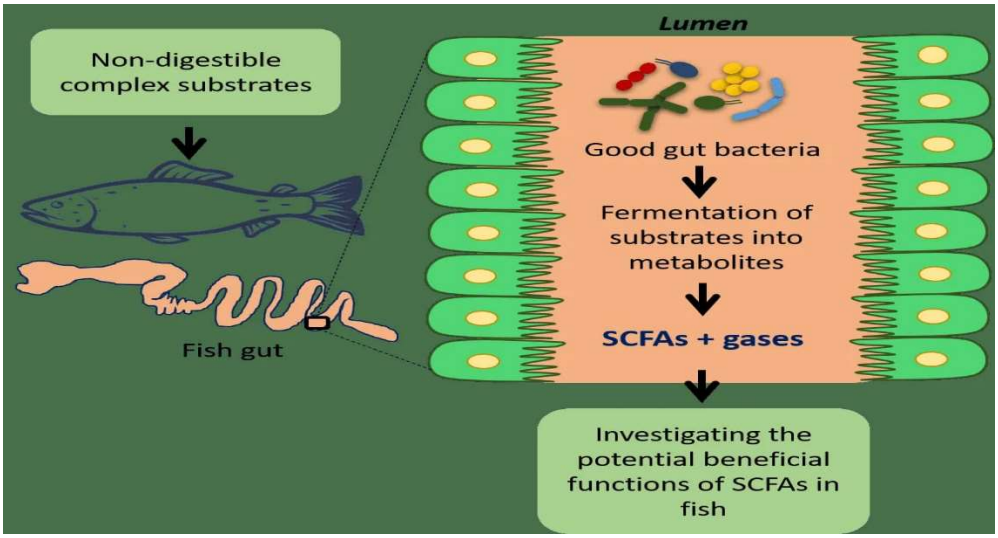
Probiotics, Prebiotics and Synbiotics

Probiotics are live microorganisms administered in appropriate amounts to provide a health benefit. In aquaculture, bacterial groups such as selected Bacillus and lactic acid bacteria have been widely investigated. Prebiotics are dietary substrates that can support selected beneficial microorganisms, whereas synbiotics combine probiotics and prebiotics. These approaches are being investigated for their potential effects on digestion, growth, immune function and disease resistance (Amenyogbe *et al*., 2024; Hoseini *et al*., 2026). However, probiotics should not automatically be considered universal replacements for antibiotics. Their effectiveness depends on appropriate strain selection, dosage, delivery method, host species and environmental conditions. A 2024 critical review emphasized the importance of host-specific selection, product stability, safety and appropriate evaluation before practical application (Amenyogbe *et al*., 2024).

Latest Research: From Probiotics to Microbiome Engineering

The field is now moving towards functional and precision-based microbiome management. Modern techniques such as 16S rRNA sequencing, metagenomics, transcriptomics and metabolomics allow researchers to study not only which microorganisms are present but also their potential functions and interactions with the host

Functional feeds are an important emerging area. Rather than providing nutrients alone, these feeds are designed to influence intestinal microbial communities and host physiological responses. Recent research has also investigated microbiome engineering and other targeted



Source: ***The Fish Site, "Gut instinct" — graphic by Dr. Shruti Gupta, discussing SCFA production by gut microbes in fish.***

Approaches for improving disease resistance (Jiang *et al*., 2026). However, these applications are still developing and require validation across different farms, seasons, diets and production systems before routine use (Khmelevtsova *et al*., 2026).

Limitations and Future Perspectives

Despite rapid progress, several challenges remain. The fish gut microbiome is highly dynamic, and microbial composition can change with species, life stage, diet, temperature, stress and environmental conditions. Therefore, results obtained in one fish species or farming system cannot

automatically be transferred to another. Another important limitation is the difference between association and causation. Finding that a particular bacterium is more abundant in healthy fish does not necessarily prove that the bacterium directly caused better health. Controlled experiments and field-scale validation are therefore essential. Safety must also be considered, particularly regarding antimicrobial-resistance genes and the ecological effects of introducing or selecting microorganisms in aquaculture systems (Khmelevtsova *et al*., 2026).

Conclusion

The fish gut microbiome represents an important link between nutrition, growth, immunity and disease resistance in aquaculture. Research in fish and shrimp species demonstrates that dietary and microbial interventions can modify gut microbial communities and influence different aspects of host health. Recent advances are moving the field from conventional probiotic supplementation towards functional feeds, multi-omics analysis and targeted microbiome management. Nevertheless, microbial interventions must be evaluated carefully because their effects are species-, strain- and environment-dependent. A better understanding of the fish gut microbiome may ultimately support the development of healthier, more efficient and sustainable aquaculture systems while reducing unnecessary dependence on antimicrobial approaches.

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HARNESSING RESISTANCE BREEDING FOR CLIMATE-RESILIENT VEGETABLE CROPS

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Abstract

Sustainable vegetable crops under climate stress had become increasingly important in the face of rising abiotic stresses such as drought, heat and chilling are major constraints to vegetable crop production worldwide, causing significant yield losses, quality deterioration and reduced crop productivity. These stresses affect important physiological, biochemical and molecular processes in plants, thereby limiting growth, photosynthesis, and reproductive performance. This article highlights the role of resistance breeding as an effective strategy for improving abiotic stress tolerance in vegetable crops as it also discusses the use of conventional and advanced breeding approaches, including marker-assisted selection (MAS), QTL mapping, genetic engineering and CRISPR-based genome editing, for developing climate-resilient cultivars. The article further explains key adaptive traits associated with drought tolerance, heat tolerance and chilling resistance, such as deep root systems, thermotolerance, osmotic adjustment, and membrane stability and the successful breeding efforts in crops like tomato (*Solanum lycopersicum*), bell pepper (*Capsicum annuum*), cabbage (*Brassica oleracea*), carrot (*Daucus carota*) and lettuce (*Lactuca sativa*) demonstrate the potential of resistance breeding in combating abiotic stresses. Overall, this article emphasizes that integrating traditional breeding with modern molecular technologies is crucial for ensuring sustainable vegetable production, improved food security and agricultural resilience under changing climatic conditions.

Introduction

Vegetable crops are highly vulnerable to environmental fluctuations, particularly extreme temperatures and inadequate soil moisture, which are among the primary factors responsible for reduced productivity in tropical and subtropical regions. The adverse effects of these stresses are expected to intensify further under changing climatic conditions and the plant responses to abiotic stresses vary depending on the crop species, developmental stage, duration and intensity of stress exposure. As to survive under such unfavourable environments, plants adopt a range of adaptive morphological, physiological, biochemical and molecular mechanisms that help minimize stress-induced damage. In recent years, resistance breeding for abiotic stress tolerance has emerged as a key strategy for improving the resilience and sustainability of vegetable production systems. This approach focuses on the identification, selection and development of vegetable genotypes capable of tolerating environmental stresses such as drought, salinity, heat and chilling while maintaining acceptable yield and quality. The plant breeders are increasingly utilizing diverse tools and technologies, including germplasm screening, conventional breeding, marker-assisted selection (MAS), genomic approaches and genetic transformation, to develop stress-tolerant cultivars (Shah et al., 2018). The development of abiotic stress-tolerant varieties begins with the identification of useful genetic traits and molecular markers associated with stress adaptation. As the important

traits often targeted in breeding programs include improved water-use efficiency, osmotic adjustment, efficient ion regulation, enhanced root architecture, membrane stability and stronger antioxidant defense systems. If one of the desirable traits are identified, they are incorporated into elite cultivars through hybridization, selection and modern molecular breeding techniques. Among these, marker-assisted selection has significantly improved breeding efficiency by enabling precise identification of plants carrying favorable genes, thereby accelerating the selection process. Similarly, advances in genetic engineering and genome editing technologies have opened new opportunities for directly introducing stress-responsive genes into vegetable crops to enhance their tolerance potential. The field evaluation under stress-prone environments remains an essential component of resistance breeding programs, as it helps determine the stability, adaptability, and performance of newly developed cultivars across different agro-climatic conditions. Furthermore, continuous advancements in molecular biology, genomics and breeding technologies are enabling researchers to refine breeding strategies for developing more resilient vegetable crops.

Overall, resistance breeding for abiotic stress tolerance represents a sustainable and long-term solution for safeguarding vegetable productivity under increasingly unpredictable environmental conditions and by the effectively utilizing plant genetic diversity alongside advanced breeding approaches, researchers and breeders are contributing significantly toward the development of climate-resilient vegetable crops capable of supporting future food and nutritional security.

Understanding Abiotic Stress Responses in Plants

Abiotic stresses vary greatly depending on region, climate and local environmental conditions as some stresses, such as drought and floods, occur unexpectedly and their intensity may differ from season to season. Certain stresses like drought and salinity can be reduced to some extent through proper crop and soil management practices, whereas stresses such as extreme temperature are more difficult to manage under field conditions. Different abiotic stresses can also influence each other. For example, lack of moisture in saline soils can further increase the harmful effects of salinity stress. The ability of plants to tolerate stress differs among crop species, varieties and growth stages and the stress occurring during the reproductive stage causes greater economic loss because it directly affects flowering, fruit set and yield.

In many cases, one stress may produce effects similar to another as salinity stress, for instance, shares several characteristics with drought stress because both reduce water availability to plants. Therefore, varieties developed for salinity tolerance may also show improved drought tolerance and understanding these stress interactions is important for developing stress-tolerant vegetable crops through resistance breeding. The major resistance breeding approaches used for improving abiotic stress tolerance in vegetable crops are outlined below:

Resistance Breeding for Drought Stress Tolerance

Drought stress is one of the most serious abiotic constraints limiting vegetable crop productivity worldwide. It occurs when water availability from rainfall and soil moisture becomes insufficient to meet the water requirement of crops during their growth and developmental stages and under such conditions, plants are unable to express their full genetic yield potential, resulting in reduced growth, poor yield and deterioration in crop quality. The drought stress develops when the rate of water loss through transpiration exceeds the amount of water absorbed by the roots, creating water deficits within plant tissues (Taiz & Zeiger, 2015). The severity of moisture stress depends on several factors, including soil type, temperature, humidity, crop growth stage and duration of stress

exposure and the different plant organs may experience varying levels of stress, with leaves being particularly affected due to their role in transpiration and photosynthesis. The prolonged water deficiency leads to reduced cell expansion, stomatal closure, impaired photosynthesis, nutrient imbalance and decreased reproductive success. As the breeding for drought resistance aims to develop vegetable cultivars capable of maintaining growth and productivity under limited water conditions and lant breeders focus on important adaptive traits such as deep and extensive root systems, improved water-use efficiency, osmotic adjustment, efficient stomatal regulation, and enhanced antioxidant activity (Cattivelli et al., 2008). The conventional breeding approaches, along with modern techniques such as marker-assisted selection (MAS), QTL mapping and genomic-assisted breeding, are increasingly being used to identify and incorporate drought-tolerant traits into elite cultivars (Shah et al., 2018). The development of drought-resilient vegetable crops is essential for sustainable agriculture, particularly under changing climatic conditions where water scarcity is becoming more frequent and severe and resistance breeding therefore plays a crucial role in improving crop adaptation, ensuring stable yields, and enhancing food security in drought-prone regions. The mechanisms and sources of drought resistance are:

A. Drought Escape

Drought escape refers to the ability of a plant to complete its life cycle before severe drought conditions occur. In this mechanism, drought-sensitive cultivars may still produce satisfactory yields by avoiding exposure to prolonged water stress. Early flowering and early maturity are important characteristics associated with drought escape, particularly in regions experiencing terminal or late-season drought stress (Levitt, 1980). This strategy enables crops to utilize available soil moisture efficiently before stress becomes severe.

B. Dehydration Avoidance

Dehydration avoidance is the capacity of plants to maintain relatively higher tissue water content even under moisture-deficient conditions. Plants achieve this through several physiological, biochemical, and metabolic adjustments that reduce water loss and improve water uptake. Important mechanisms include stomatal regulation, reduced transpiration, deep root development, osmotic adjustment, and efficient water-use efficiency (Taiz & Zeiger, 2015). Maintenance of cell turgor is considered one of the key indicators of dehydration avoidance. Plants may adopt either “water-saving” mechanisms by limiting transpiration or “water-spending” mechanisms by enhancing water absorption from deeper soil layers.

C. Dehydration Tolerance

Dehydration tolerance is the ability of plants to survive and maintain cellular functions even after substantial loss of water from tissues. Under severe dehydration, plants experience reduced water activity, increased solute concentration, membrane instability, and metabolic disturbances. However, tolerant genotypes exhibit comparatively lower physiological and biochemical damage than susceptible ones when exposed to similar stress intensity (Farooq et al., 2009). The protective mechanisms such as osmolyte accumulation, antioxidant activity, membrane stabilization, and stress-responsive proteins help plants tolerate cellular dehydration.

Sources of Drought Resistance:

i) Cultivated Varieties

Improved cultivars and elite breeding lines often possess considerable genetic variability for drought resistance traits. These materials provide useful sources for incorporating adaptive traits into high-yielding vegetable cultivars.

ii) Landraces

Traditional landraces adapted to drought-prone environments serve as valuable genetic resources for drought tolerance. These locally adapted genotypes have evolved through both natural and farmer selection under harsh environmental conditions. Although they may possess some undesirable traits, they remain important sources of stress-adaptive genes (Ceccarelli & Grando, 1996).

iii) Wild Relatives

Wild species growing naturally in arid and semi-arid habitats are considered excellent sources of drought and salinity resistance. Their ability to survive under extreme environmental conditions makes them valuable genetic resources in resistance breeding programs.

iv) Transgenes

Modern biotechnological approaches have enabled the identification, isolation, and transfer of stress-responsive genes into crop plants. Transgenic approaches involving genes associated with osmotic adjustment, antioxidant defense, and proline accumulation have shown promising results in improving drought tolerance. Among these, proline accumulation plays an important role in maintaining cell stability and sustaining plant growth under water-deficit conditions (Ashraf & Foolad, 2007).

Methods and Strategies in Drought Resistance Breeding

Incorporating drought resistance along with high genetic yield potential has become one of the major objectives of modern vegetable breeding programs. Since crops are often exposed to fluctuating environmental conditions, breeders must integrate selection for stress tolerance with the evaluation of yield performance under both stress and favorable environments. This helps in developing cultivars that can maintain stable productivity under water-limited conditions without compromising yield under normal cultivation practices.

The major approaches used in resistance breeding for drought tolerance are discussed below:

a) Adaptation to Specific Environments

In this approach, cultivars are specifically developed for regions frequently affected by moisture deficit or drought conditions. Selection and evaluation of breeding materials are carried out under stress environments to identify genotypes capable of surviving and producing acceptable yields under limited water availability. Traits such as deep root systems, efficient water-use efficiency, osmotic adjustment, and reduced transpiration are commonly targeted in these breeding programs. However, varieties developed exclusively for drought-prone environments may not perform optimally under favorable moisture conditions because they are primarily adapted to stress situations.

b) Adaptation to Variable Environments

This strategy focuses on combining drought tolerance with high yield potential and wider adaptability. Breeding lines are evaluated under both stress and non-stress conditions to identify stable genotypes capable of performing consistently across diverse environments. Selection is mainly based on yield performance, yield-contributing traits, stress tolerance efficiency, and overall stability. This approach is considered more practical and sustainable because it enables the development of cultivars that can withstand intermittent drought stress while still responding positively to favorable environmental conditions.

Modern resistance breeding programs further integrate molecular tools such as marker-assisted selection (MAS), genomic selection, and QTL mapping to improve breeding efficiency and accelerate the development of drought-resilient vegetable cultivars. These advanced techniques help breeders identify stress-responsive genes and incorporate them into elite breeding materials more precisely and rapidly.

Resistance Breeding for Salinity Stress Tolerance

Soil salinity is considered one of the most serious abiotic stresses limiting agricultural productivity and sustainability worldwide (Boyer, 1982). Increasing soil salinization, particularly in arid and semi-arid regions, has become a major concern due to climate change, improper irrigation practices, low rainfall, excessive fertilizer use, and poor drainage systems (Munns & Tester, 2008). It has been estimated that salinity-affected areas may account for nearly 30% loss of arable land by 2025, and this figure could increase to almost 50% by 2050 if suitable management and breeding strategies are not adopted (Wang et al., 2003). These such trends pose a significant threat to global food security and sustainable vegetable production and the accumulation of excessive soluble salts in the root zone creates osmotic and ionic stress conditions that adversely affect plant growth and development. The high salt concentrations reduce the ability of plants to absorb water, resulting in physiological drought even when adequate soil moisture is available (Taiz & Zeiger, 2015). In addition, salinity stress causes mineral imbalances through ion toxicity and nutrient deficiencies, mainly due to excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions. These ions interfere with the uptake and transport of essential nutrients such as potassium, calcium, and magnesium, thereby disturbing important physiological and metabolic processes in plants (Munns & Tester, 2008). Both conventional breeding methods and advanced molecular approaches, including marker-assisted selection (MAS) and genetic engineering, are being used to develop salinity-tolerant vegetable cultivars. These approaches play a vital role in sustaining crop production in salt-affected soils and ensuring agricultural resilience under changing climatic conditions.

Salinity stress also affects seed germination, root development, photosynthesis, enzyme activity, and reproductive growth, ultimately leading to significant reductions in yield and crop quality. Vegetable crops are particularly sensitive to salinity stress during early growth and reproductive stages. Therefore, the development of salinity-tolerant cultivars through resistance breeding, molecular approaches, and improved agronomic management practices has become essential for sustaining crop productivity under saline environments.

Breeding Approaches for Salinity Stress Tolerance

In India, the Central Soil Salinity Research Institute (CSSRI), Karnal plays a major role in developing salinity-tolerant crop varieties. The resistance breeding for salinity tolerance focuses on improving the ability of plants to survive and produce satisfactory yields under salt-affected conditions through conventional and modern breeding approaches.

i) Selection

The selection has been widely used to identify and develop salinity-tolerant lines with better growth and yield under saline environments. Breeding materials are screened under controlled salinity conditions to select superior genotypes possessing adaptive traits such as ion regulation, osmotic adjustment and membrane stability.

ii) Hybridization

Hybridization is an important method for combining salinity tolerance from one parent with the high yield potential of another. In segregating generations, selection is carried out under both saline

and normal conditions to identify stable and productive genotypes. Evaluation under varying salinity levels helps breeders identify lines with improved stress tolerance and yield stability.

iii) Interspecific Hybridization

Wild relatives are valuable sources of salinity tolerance genes. In tomato, salinity-resistant wild species such as *Lycopersicon cheesmanii* have been used to transfer stress-tolerant traits into cultivated varieties through interspecific hybridization. Such approaches broaden the genetic base for salinity resistance breeding.

iv) Cell Selection and Somaclonal Variation

Cell and tissue culture techniques are also used to develop salt-tolerant plants and the somaclonal variation generated through callus culture can help identify stress-tolerant cell lines capable of regenerating into resistant plants.

v) Genetic Engineering

The modern biotechnological approaches, including genetic engineering and genome editing, are being used to introduce genes associated with osmoregulation, ion transport, antioxidant activity and polyamine biosynthesis to improve salinity and drought tolerance in vegetable crops.

Constraints in Breeding for Salinity Tolerance

The breeding for salinity tolerance is difficult because the trait is genetically complex and controlled by multiple genes. As creating reliable and uniform salinity conditions for screening breeding materials is expensive and technically challenging. In addition, the physiological and molecular basis of salinity tolerance is not fully understood, making selection and genetic improvement more complicated. Despite these limitations, integration of conventional breeding with molecular and genomic tools continues to improve the development of salinity-tolerant vegetable cultivars.

Resistance Breeding for Heat and Cold Stress Tolerance

The temperature stress has emerged as a major challenge to global crop production due to changing climatic conditions and increasing global warming and rising concentrations of greenhouse gases such as carbon dioxide (CO_2), methane, nitrous oxide and chlorofluorocarbons have contributed significantly to fluctuations in global temperature. According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures are expected to increase steadily in the coming decades, posing serious threats to agricultural productivity (Jones et al., 1999). The vegetable crops are particularly sensitive to temperature extremes, which adversely affect plant growth, development, yield and quality. As the temperature plays a vital role in regulating physiological and biochemical activities in plants. Most metabolic processes increase with temperature only within an optimum range, commonly expressed by the Q10 concept, which describes the rate of biochemical reactions with a 10°C increase in temperature. However, when temperatures rise above or fall below the optimum range, normal plant functions become disrupted, resulting in stress injury or even plant death in sensitive species (Taiz & Zeiger, 2015). The extent of damage depends on crop species, genotype, growth stage, duration of stress exposure and environmental conditions.

Temperature stress is generally classified into three categories:

- **Heat stress**
- **Chilling stress**
- **Freezing stress**

Heat Stress Tolerance

Heat stress occurs when temperatures exceed the optimum threshold required for normal plant growth and development. High temperatures negatively affect photosynthesis, pollen viability, enzyme activity, membrane stability, and reproductive processes, ultimately leading to flower drop, poor fruit set, reduced yield, and inferior crop quality (Wahid et al., 2007). In vegetable crops, heat stress is particularly damaging during flowering and fruit development stages.

Resistance breeding for heat tolerance focuses on developing cultivars with improved thermotolerance mechanisms such as efficient canopy cooling, heat shock protein production, membrane stability, and enhanced antioxidant activity. Traits like early maturity, efficient transpiration, and pollen fertility under high temperatures are also considered important in breeding programs. Modern approaches such as marker-assisted selection (MAS), QTL mapping, and genomic-assisted breeding are increasingly being utilized to identify and incorporate heat-tolerant genes into elite vegetable cultivars.

Chilling and Freezing Stress

Cold stress includes chilling stress and freezing stress. Chilling stress occurs at low but non-freezing temperatures, while freezing stress develops when temperatures fall below 0°C, causing ice crystal formation within plant tissues. Low-temperature stress disrupts membrane integrity, enzyme activity, water uptake, and metabolic functions, leading to stunted growth, chlorosis, and tissue damage (Thomashow, 1999). Vegetable crops of tropical and subtropical origin are generally more susceptible to chilling injury.

Breeding for cold tolerance aims to develop genotypes capable of maintaining normal physiological activities under low-temperature conditions. Important traits targeted in resistance breeding include membrane stability, accumulation of compatible solutes, antifreeze proteins, cold-responsive gene expression, and improved recovery after stress exposure. Conventional breeding, along with molecular breeding and transgenic approaches, has significantly improved the development of heat- and cold-tolerant vegetable cultivars suitable for diverse climatic conditions.

Physiological Basis of Heat and Cold Stress Tolerance

Heat Stress Tolerance

Heat stress tolerance in plants involves both heat avoidance and heat tolerance mechanisms. Heat avoidance refers to the ability of plants to prevent excessive rise in internal tissue temperature under high-temperature conditions. One of the major mechanisms involved in heat avoidance is transpiration cooling, through which plants dissipate excess heat by water loss from leaves (Wahid et al., 2007). However, under limited soil moisture conditions, heat avoidance becomes closely associated with dehydration avoidance because reduced water availability restricts transpiration. Leaf characteristics such as pubescence, waxy coatings, leaf orientation, and insulating bark also contribute to reducing heat absorption by reflecting solar radiation and lowering canopy temperature. Heat tolerance refers to the ability of certain genotypes to maintain normal growth and physiological activities even under elevated internal temperatures. This tolerance is mainly associated with cellular and biochemical stability during stress conditions. Plants exposed to mild high temperatures may acquire increased resistance to subsequent severe heat stress through a process known as heat hardening or heat acclimation (Hall, 2001). During this process, plants activate protective mechanisms such as heat shock proteins, antioxidant enzymes, membrane stabilization, and maintenance of enzyme activity.

Resistance breeding for heat tolerance focuses on traits such as membrane stability, pollen fertility under high temperatures, efficient photosynthesis, canopy cooling, and enhanced antioxidant defense systems. Modern breeding tools such as marker-assisted selection (MAS), QTL mapping, and genomic-assisted breeding are increasingly used to develop heat-tolerant vegetable cultivars.

Chilling Stress Resistance

Chilling stress mainly affects tropical and subtropical crops that are sensitive to low but non-freezing temperatures. Chilling injury can occur at both whole-plant and subcellular levels, severely affecting plant growth and productivity (Thomashow, 1999).

Chilling Stress at the Plant Level

At the plant level, chilling stress negatively affects seed germination, seedling establishment, vegetative growth, flowering, fruit set, yield, and fruit quality. Low temperatures reduce metabolic activities, leading to poor germination, chlorosis, wilting, stunted growth, and reduced reproductive success. Seedling establishment and photosynthesis after germination are considered highly sensitive stages to chilling injury. Low temperatures also reduce root growth, limiting water and nutrient uptake. In crops such as tomato, chilling stress often causes pollen sterility, flower abnormalities, poor fruit set, and malformed fruits (Taiz & Zeiger, 2015).

Chilling Stress at the Subcellular Level

At the cellular level, chilling stress primarily affects membrane stability and interferes with important physiological processes such as chlorophyll synthesis, photosynthesis, respiration, and chloroplast functioning. Chilling injury also promotes the accumulation of reactive oxygen species (ROS), particularly hydrogen peroxide (H_2O_2), resulting in oxidative stress and membrane damage (Lyons, 1973). In chilling-sensitive plants, inhibition of catalase activity may prevent detoxification of H_2O_2, thereby increasing cellular injury.

Chilling Tolerance

Chilling tolerance is the ability of certain genotypes to survive and perform better under low-temperature conditions compared to sensitive cultivars. Plants may acquire improved chilling resistance through chill hardening, where prior exposure to moderately low temperatures enhances tolerance to subsequent chilling stress. Important adaptive mechanisms include membrane stabilization, osmolyte accumulation, antioxidant activity, and expression of cold-responsive genes (Thomashow, 1999). Resistance breeding for chilling tolerance aims to develop cultivars capable of maintaining growth, flowering, and yield under low-temperature environments. Conventional breeding, combined with molecular breeding and genomic approaches, has significantly contributed to the development of heat- and cold-tolerant vegetable cultivars suitable for changing climatic conditions.

Resistance Breeding for Mineral Toxicity and Nutrient Stress

The mineral stress occurs when plants are exposed to either excessive accumulation of toxic minerals or deficiency of essential nutrients in the soil, resulting in adverse effects on plant growth, development, and productivity. Proper nutrient absorption by plant roots is essential for maintaining normal physiological and metabolic activities and the uptake of mineral nutrients generally follows the Michaelis-Menten relationship, where nutrient absorption depends on ion concentration and root absorption efficiency (Marschner, 2012). As the essential nutrients such as nitrogen (N), sulfur (S), calcium (Ca) and magnesium (Mg) are mainly transported to roots through

mass flow, whereas nutrients like phosphorus (P), potassium (K), zinc (Zn) and manganese (Mn) are often limited in availability under deficient soil conditions and the plants respond to mineral stress through several adaptive mechanisms. Under nutrient-deficient conditions, plants often enhance root growth relative to shoot growth in order to increase nutrient absorption efficiency as the changes in root membrane permeability and secretion of organic acids by roots also help improve nutrient availability, particularly for phosphorus, zinc, and manganese in deficient soils (Taiz & Zeiger, 2015). In addition, plants may activate specific transport proteins and stress-responsive metabolic pathways to maintain ionic balance and minimize toxicity effects.

Mineral stress is generally classified into two major categories:

- **Mineral deficiency stress**
- **Mineral toxicity stress**

Mineral deficiency stress develops when essential nutrients are unavailable in sufficient quantities, leading to poor growth, chlorosis, reduced photosynthesis, and lower yield. In contrast, mineral toxicity stress occurs due to excessive accumulation of ions such as sodium, aluminium, boron, or heavy metals, which interfere with cellular metabolism and damage plant tissues. The resistance breeding for mineral stress tolerance focuses on developing cultivars with improved nutrient-use efficiency, enhanced root architecture, ion regulation, and tolerance to toxic elements. As the conventional breeding methods, along with molecular and genomic approaches, are increasingly being used to identify and incorporate mineral stress tolerance traits into vegetable crops for sustainable production under problematic soil conditions.

Plant Adaptation to Mineral Deficiency

The certain plant genotypes exhibit comparatively lower adverse effects under mineral-deficient conditions than other genotypes of the same species and such genotypes are known as mineral deficiency-resistant or mineral-efficient genotypes. These plants possess a greater ability to absorb, utilize and transport essential nutrients efficiently to different plant tissues even when nutrient availability in the soil is limited (Marschner, 2012). As a result, they are able to maintain normal growth and physiological functions by preventing severe nutrient deficiency within plant tissues. This mechanism is generally referred to as mineral deficiency avoidance.

In some cases, certain genotypes are capable of tolerating low internal concentrations of essential nutrients while sustaining vital metabolic activities with comparatively less damage. This phenomenon is known as mineral deficiency tolerance, although it is considered less common than nutrient efficiency mechanisms. The development of mineral-efficient cultivars through resistance breeding is important for improving crop productivity under nutrient-deficient soil conditions and reducing dependence on excessive fertilizer application**.**

Genetic Resources for Resistance to Mineral Deficiency

Genetic variability for resistance to mineral deficiency stress is available in several plant genetic resources, which serve as valuable sources in resistance breeding programs. These resources include:

- ✓ Cultivated varieties
- ✓ Landraces or local cultivars
- ✓ Wild and related species
- ✓ Mutants

In many crop species, cultivated varieties developed or adapted to nutrient-deficient regions possess useful traits for mineral stress tolerance. Such varieties are often capable of efficient nutrient uptake, transport, and utilization under limited nutrient availability. For example, the 'Rutgers' tomato variety has shown better adaptation under certain mineral-deficient conditions. These improved cultivars provide readily usable genetic material for breeding programs aimed at developing nutrient-efficient vegetable crops. The landraces and traditional local varieties are also important genetic resources because they have evolved naturally under nutrient-stressed environments over long periods of time. As a result, they often possess adaptive traits such as extensive root systems, improved nutrient-use efficiency, and enhanced tolerance to poor soil conditions. Similarly, wild relatives and related species adapted to problematic soils can serve as valuable donors of stress-tolerant genes for crop improvement programs. Mutants generated through natural variation or induced mutagenesis have also contributed to the identification of genes associated with nutrient efficiency and mineral stress tolerance. These genetic resources are increasingly being utilized in conventional breeding, molecular breeding, and genomic-assisted approaches to develop vegetable cultivars capable of maintaining productivity under nutrient-deficient conditions. The effective utilization of such diverse genetic resources plays a crucial role in sustainable agriculture by reducing fertilizer dependency and improving crop adaptation to marginal soils.

Constraints in Breeding for Mineral Stress Resistance

- Mineral toxicity and nutrient deficiency vary across different soil types and locations, making it difficult to develop universally adaptable varieties.
- Aluminium and manganese toxicities often occur together in acidic soils, complicating resistance breeding.
- Interactions between toxic elements and essential nutrients such as Ca, P, and Mg can affect accurate selection of tolerant genotypes.
- Screening under controlled conditions like hydroponics is costly and requires technical expertise.
- Breeding lines must be evaluated under both stress and non-stress conditions, increasing time and expenditure.
- Mineral deficiency symptoms may not always be visible, requiring chemical and biochemical analyses for proper evaluation.
- Mineral stress tolerance is usually controlled by multiple genes and influenced by environmental conditions, making breeding more complex.

Modern Breeding Strategies for Climate-Resilient Vegetable Crops

1. Marker-Assisted Selection (MAS)

The Marker-assisted selection (MAS) has become an important molecular breeding tool for improving abiotic stress tolerance in vegetable crops as this approach uses DNA markers closely associated with desirable genes or quantitative trait loci (QTLs), allowing breeders to identify superior genotypes more efficiently and accurately than conventional field selection methods (Collard & Mackill, 2008). As MAS shortens the breeding cycle and enhances the precision of selecting stress-tolerant lines. In vegetable breeding programs, MAS has been extensively applied for developing cultivars resistant to drought, salinity, and heat stress. In tomato (*Solanum lycopersicum*), markers associated with root traits and water-use efficiency have been utilized to improve drought tolerance. Similarly, salinity and temperature-tolerant genotypes have been

identified in crops such as chilli (*Capsicum annuum*) and cucumber (*Cucumis sativus*). The integration of molecular markers into breeding programs has greatly contributed to the development of climate-adaptive vegetable cultivars.

2. Quantitative Trait Loci (QTL) Mapping

Quantitative Trait Loci (QTL) mapping is an advanced genomic approach used to identify specific chromosomal regions associated with complex quantitative traits related to abiotic stress tolerance. Since most stress-responsive traits such as drought tolerance, salinity resistance, heat tolerance, root architecture, osmotic adjustment, membrane stability, antioxidant activity and nutrient-use efficiency are controlled by multiple genes, QTL analysis plays a crucial role in understanding their genetic basis (Ashraf, 2010). This technique enables breeders to locate genomic regions governing important adaptive traits and facilitates the precise selection of stress-tolerant genotypes in breeding programs. QTL mapping has become an essential tool in modern resistance breeding because it helps bridge the gap between genotype and phenotype under stress conditions. By identifying genomic regions associated with stress adaptation, breeders can accelerate the development of climate-resilient vegetable cultivars through marker-assisted breeding and genomic-assisted selection. QTL analysis also improves the efficiency of selecting complex traits that are difficult to evaluate solely through conventional phenotypic screening.

In vegetable crops, several important QTLs associated with drought, heat, chilling, and salinity tolerance have been identified in tomato (*Solanum lycopersicum*), eggplant (*Solanum melongena*), lettuce (*Lactuca sativa*), chilli and pepper (*Capsicum annuum*), cucumber (*Cucumis sativus*), and watermelon (*Citrullus lanatus*). In tomato, QTLs related to salt tolerance, root growth, water-use efficiency, and fruit quality have been extensively studied. Similarly, heat tolerance-associated QTLs controlling pollen viability, fruit set, and membrane stability have been reported in chilli and pepper. In lettuce and cucumber, genomic regions linked with improved stress adaptation and nutrient efficiency have also been identified. The identification and utilization of stress-related QTLs provide valuable opportunities for developing superior vegetable cultivars with improved adaptability, stable yield performance, and enhanced resilience under changing climatic conditions. Integration of QTL mapping with advanced molecular tools such as marker-assisted selection (MAS), genomic selection, and CRISPR-based genome editing is further accelerating the development of next-generation climate-smart vegetable crops.

3. CRISPR-Based Genome Editing

The CRISPR/Cas genome editing has emerged as one of the most advanced and precise technologies for improving abiotic stress tolerance in vegetable crops. This revolutionary breeding tool enables targeted modification of specific genes associated with important stress-responsive traits such as drought tolerance, salinity resistance, heat tolerance and cold adaptation. As Unlike conventional transgenic approaches, CRISPR technology allows precise editing of native plant genes without necessarily introducing foreign DNA into the genome, making it faster, more efficient, and highly reliable for crop improvement programs (Jaganathan et al., 2018). The CRISPR/Cas system functions by identifying and modifying specific DNA sequences responsible for stress-related physiological and biochemical responses. Through targeted gene editing, breeders can improve important adaptive traits including root architecture, water-use efficiency, ion transport, osmotic adjustment, antioxidant defense mechanisms, and stress-signaling pathways. This technology

significantly reduces the time required for developing stress-tolerant cultivars compared to traditional breeding methods.

In vegetable crops, CRISPR-based genome editing has been successfully explored in tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), watermelon (*Citrullus lanatus*), potato (*Solanum tuberosum*), and pepper (*Capsicum annuum*) for enhancing tolerance to drought, salinity, and temperature extremes. In tomato, CRISPR has been utilized to improve heat tolerance, fruit quality, and water-use efficiency, while in cucumber and watermelon, gene editing has contributed to improved salinity and drought adaptation. Similarly, stress-responsive genes associated with root development, photosynthetic efficiency, and membrane stability have been targeted to improve overall plant resilience under adverse environmental conditions. An important advantage of CRISPR technology is its ability to generate precise genetic changes with minimal unintended effects, thereby improving breeding accuracy and accelerating the development of superior cultivars. Furthermore, CRISPR-based breeding can be effectively integrated with marker-assisted selection (MAS), QTL mapping and genomic selection to strengthen modern resistance breeding programs. With increasing climate variability and environmental stress, CRISPR/Cas genome editing holds tremendous potential for developing next-generation climate-smart vegetable crops capable of maintaining stable productivity, improved nutritional quality, and better adaptation under changing agro-climatic conditions. This technology is expected to play a transformative role in ensuring sustainable vegetable production and global food security in the future.

Vegetable cultivars resistant or tolerant to major abiotic stress conditions (Mishra *et al*., 2021)

Vegetable Crop	Variety	Important Stress-Tolerant Traits
Tomato	Pusa Sheetal	Good fruit set under low temperature
	Arka Vikas	Tolerant to moisture stress
	Pusa Sadabahar	Adapted to a wide temperature range
Brinjal	Punjab Chamkila	Suitable for summer and autumn season
	Punjab Barsati	Performs well during rainy season
	Krishna (F1 Hybrid)	Tolerant to adverse climatic conditions
Chilli	Arka Lohit	Tolerant to moisture stress
	Phule Sai	Performs well under rainfed conditions
	Phule Jyoti	Resistant to waterlogging
Okra	Kiran	Suitable for rainfed cultivation
	Salkeerthi	Adapted to rainfed conditions
	Aruna	Suitable for early rainfed crop
Potato	Kufri Kundan	Frost tolerant
	Kufri Sheetman	Highly resistant to frost
	Kufri Surya	Heat tolerant
Cucumber	Sheetal	Performs well under high rainfall
Muskmelon	Hissar Madhur	Early maturity and reduced disease incidence
Watermelon	Sugar Baby	Drought tolerant
Pea	VL Agethi Matar-7	Escapes powdery mildew
Cowpea	Arka Garima	Tolerant to heat and drought
Radish	Pusa Reshmi	Adapted to higher temperatures
Spinach	Pusa Harit	Low chilling requirement and alkaline soil tolerance

Vegetable Crop	Variety	Important Stress-Tolerant Traits
Lettuce	Great Lakes	Moderately heat tolerant
	Pusa Ageti	Suitable for cooler conditions

Improvement of Vegetable Crops Through Resistance Breeding

The resistance breeding had played an important role in improving the adaptability of vegetable crops to various abiotic stresses such as drought, salinity, heat, chilling and moisture stress as in tomato (*Solanum lycopersicum*), significant advancements have been made in developing stress-tolerant cultivars through the selection of traits like extensive root systems, improved water-use efficiency, better pollen fertility and stable fruit setting under elevated temperatures. Some varieties such as *Arka Vikas* and *Pusa Sadabahar* are known for their better performance under moisture-limited and fluctuating temperature conditions.

In bell pepper (*Capsicum annuum*), breeding programs have concentrated on enhancing tolerance to drought, high temperature, and excess soil moisture as improved cultivars such as *Arka Lohit* and *Phule Jyoti* have shown better yield stability and adaptability under stressful environmental conditions. Likewise, breeding efforts in cabbage (*Brassica oleracea*) have focused on developing varieties capable of tolerating temperature fluctuations and moisture stress, resulting in improved head development and productivity.

For carrot (*Daucus carota*), resistance breeding has mainly targeted salinity and temperature tolerance to maintain root quality and yield under unfavourable environments. In lettuce (*Lactuca sativa*), breeders have developed cultivars with enhanced heat tolerance and delayed bolting, making cultivation possible under relatively warmer climatic conditions and the Variety like *Great Lakes* had exhibited moderate adaptability to heat stress and changing environmental conditions.

The combination of conventional breeding methods with advanced molecular techniques such as marker-assisted selection (MAS), QTL mapping and genome editing has greatly improved the efficiency of developing climate-resilient vegetable cultivars. These successful breeding achievements clearly demonstrate the potential of resistance breeding in enhancing crop resilience, sustaining vegetable production and supporting food security under changing climatic scenarios (Ashraf, 2010; Collard & Mackill, 2008).

Conclusion

Ensuring sustainable vegetable production under changing climatic conditions has become one of the major priorities of modern agriculture as the environmental stresses such as drought, salinity, heat, chilling and mineral imbalance severely affect plant growth, physiological processes, yield stability, and crop quality. Therefore, the development of stress-resilient vegetable cultivars is essential for maintaining productivity and ensuring global food and nutritional security. The resistance breeding has proven to be an effective and eco-friendly approach for improving abiotic stress tolerance in vegetable crops. The integration of conventional breeding methods with advanced molecular technologies such as marker-assisted selection (MAS), QTL mapping, genetic engineering, and CRISPR/Cas-based genome editing has accelerated the identification and incorporation of stress-tolerant traits into elite cultivars The traits such as deep root systems, osmotic adjustment, thermotolerance, membrane stability, and efficient nutrient utilization play a crucial role in helping plants withstand adverse environmental conditions. As successful breeding efforts in crops such as tomato (*Solanum lycopersicum*), bell pepper (*Capsicum annuum*), cabbage

(*Brassica oleracea*), carrot (*Daucus carota*), and lettuce (*Lactuca sativa*) clearly demonstrate the potential of resistance breeding in developing climate-resilient vegetable crops. The combined application of traditional knowledge and modern genomic tools will continue to strengthen breeding programmes aimed at improving adaptability, yield stability, and stress tolerance. Overall, harnessing resistance breeding strategies offers a sustainable pathway for enhancing agricultural resilience, securing vegetable production and supporting future food security in the era of climate change.

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HARNESSING SOLAR POWER FOR SUSTAINABLE SHRIMP FARMING

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Abstract
Shrimp culture is an energy-intensive aquaculture practice requiring electricity for various farming operations. Rising energy costs, dependence on grid electricity and diesel, and the need to reduce environmental impacts have increased interest in renewable-energy solutions. Solar photovoltaic (PV) technology offers considerable potential for shrimp farming due to its scalability, modularity and suitability for regions with abundant sunlight. Solar PV systems can power aerators, pumps, automatic feeders, lighting, security and monitoring devices. Integration with energy-efficient equipment, battery storage, automated controls and Internet of Things (IoT) technologies can further improve energy efficiency, reduce operating costs and enhance farm sustainability. Solar-powered systems can also reduce dependence on conventional energy sources and associated greenhouse-gas emissions. Thus, integrating solar PV with smart and energy-efficient technologies provides a promising pathway towards more sustainable, economically viable and climate-resilient shrimp farming.

Keywords: Energy efficiency; Solar energy; Shrimp aquaculture; Solar aeration; Solar feeders

Introduction

Shrimp farming has become one of the most important and rapidly expanding components of global aquaculture. The Pacific white shrimp (Penaeus vannamei) dominates farmed shrimp production because of its rapid growth, adaptability to intensive culture and suitability for commercial production. Global farmed shrimp production was estimated at about 5.6 million metric tonnes (MMT) in 2023, with Ecuador, China, India, Vietnam and Indonesia together contributing approximately 74% of global production. India is also a major producer and exporter, with Andhra Pradesh, Gujarat, Odisha and Tamil Nadu playing important roles in shrimp aquaculture. The intensification of shrimp farming, however, has increased dependence on electricity and fuel. Aeration, pumping, feeding, water exchange, lighting and farm monitoring require a continuous and reliable energy supply. In shrimp culture, energy costs may account for about 15–30% of operational expenditure, while aeration alone can contribute around 20–25% of production costs. In remote coastal areas, diesel generators are often used when grid electricity is unreliable. This dependence creates several concerns. Rising electricity and fuel prices increase production costs, while power interruptions can quickly reduce dissolved oxygen and threaten shrimp survival. Fossil-fuel-based electricity also contributes to greenhouse gas emissions. These challenges highlight the need to improve energy efficiency and diversify farm energy sources. Solar energy, particularly solar photovoltaic (PV) technology, offers an attractive pathway towards more reliable, economical and climate-resilient shrimp production.

Solar Energy: A Practical Opportunity for Shrimp Farms

Solar energy is particularly suitable for shrimp farming because farms are generally located in open coastal or rural areas with good solar exposure and adequate space for photovoltaic installations. India receives abundant solar radiation across many regions and experiences sunny days annually in most areas. The growth of solar infrastructure, decreasing technology costs, and advancements in photovoltaic efficiency have strengthened the feasibility of decentralized solar power. India's solar development has been supported by major policy initiatives, and the national objective of achieving non-fossil-fuel capacity by 2030, along with net-zero emissions by 2070, underscores the critical role of renewable energy. For shrimp farmers, solar photovoltaic (PV) systems can serve not only as a substitute for grid electricity but also as a pivotal energy source. When paired with battery storage, efficient machinery, automation, and digital monitoring, it can establish the energy backbone of a smart farm. Solar energy can power aerators, feeders, pumps, sensors, lighting, surveillance systems, and Internet of Things (IoT)-driven farm management platforms. This holistic strategy can enhance energy security while minimizing ongoing energy costs and environmental effects.

Why Solar Energy Matters to Shrimp Farmers

Solar energy presents numerous economic, operational, and environmental advantages for shrimp farming. It reduces reliance on grid electricity and diesel, decreases ongoing energy expenses, and offers long-term financial savings. Solar power can effectively supply power to essential equipment, including aerators, pumps, feeders, and monitoring systems, while battery storage enhances energy security during nighttime and power interruptions. Integration with IoT and automation can further improve farm efficiency. From an environmental perspective, solar energy lessens dependence on fossil fuels and the related greenhouse gas emissions, thereby promoting a more resource-efficient and climate-resilient approach to shrimp farming.

Applications of Solar Energy in Shrimp Farming

Solar photovoltaic (PV) systems can be installed around ponds, on farm buildings or on suitable structures to generate electricity for farm operations. The energy generated can be used directly during daylight hours or stored in batteries for use at night and during periods of low solar radiation. This serves as an alternative to grid electricity and diesel generators, especially in remote shrimp-farming areas where reliable electricity supply may be limited. Solar energy has diverse applications in shrimp farming, ranging from electricity generation to aeration, pumping, feeding, water-quality monitoring, lighting and farm security. Aeration is one of the most important applications of solar energy, as adequate dissolved oxygen is essential for shrimp growth and survival. Solar-powered aerators can function using electricity produced by PV systems, while battery-supported systems can supply power after sunset. By integrating solar energy with energy-efficient aerators, dissolved oxygen sensors and automated controls can further improve efficiency by adjusting aeration according to actual oxygen requirements. Additionally, solar energy can support water pumps and circulation systems utilized for water exchange, and other farming operations, thereby reducing reliance on conventional electricity. Solar energy can also improve feeding and water-quality management. Solar-powered automatic feeders can dispense feed at predetermined intervals and quantities, minimizing labour requirements and improving feeding consistency. When linked with sensors and digital farm-management systems, feeding can be more effectively adjusted according to shrimp growth and feeding responses. Solar-powered sensors can continuously monitor parameters such as dissolved oxygen and temperature, with data transmitted through mobile or cloud-based platforms. Such systems can facilitate timely management decisions and, when

connected with automated equipment, enable operations such as aeration to adapt to changing pond conditions.

Another useful application is solar-powered lighting, surveillance and farm security. Solar LED lights can illuminate areas around farm entrances, walkways, pond embankments, storage areas and equipment shed thereby enhancing and worker safety. Additionally, motion-activated lighting can further minimize energy consumption. Battery-supported solar systems can also operate CCTV cameras, motion sensors, alarms and communication devices, providing greater security, particularly during nighttime and power interruptions. An emerging opportunity is the integration of solar PV with aquaculture through aquavoltaic and floating photovoltaic systems. Solar panels installed above, adjacent to or on suitable water surfaces can generate renewable electricity while optimizing the use of available farm space. Partial shading may also help to reduce excessive heating and evaporation; however, excessive shading could affect pond productivity and ecological conditions. Therefore, panel coverage and system design require careful consideration. Overall, combining solar PV with battery storage, energy-efficient equipment, sensors, IoT and automation can transform solar energy from merely an alternative power source into an important component of smart, energy-efficient and resilient shrimp farming.



Solar photovoltaic (PV) systems in shrimp farms

Challenges and Future Directions

Although solar energy has significant potential, its implementation in shrimp farming encounters challenges such as high initial investment, battery maintenance, variable solar availability and the need for suitable installation space and technical know-how. Additionally, coastal conditions may cause corrosion, while floating systems require durable structures and careful management of panel coverage and shading. Future efforts should focus on integrating solar PV with IoT, automation, smart aeration and improved battery storage, as well as to refine aquavoltaic and floating PV systems. Furthermore, comprehensive long-term research on economic feasibility, environmental impacts, system durability, and recycling of photovoltaic and battery components is essential to facilitate sustainable adoption.

Conclusion

Solar energy offers a practical pathway towards efficient, economical and climate-resilient shrimp farming. Solar PV can support aeration, pumping, feeding, monitoring, lighting and security, with greater benefits when integrated with energy-efficient equipment, battery storage, IoT and automation. Aquavoltaic and floating PV systems further expand opportunities for combining renewable energy with aquaculture. Overall, integrated solar-powered systems can lower operational expenses and environmental impacts, improve energy security and strengthen the resilience of shrimp farming.

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HIGH DENSITY PLANTING SYSTEM IN HORTICULTURE CROPS: SCOPE, PRODUCTION TECHNOLOGY AND ECONOMICS FOR TELANGANA STATE

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Abstract
High Density Planting System (HDPS) is an intensive orcharding technique that increases plant population per unit area through use of dwarf varieties, rootstocks, canopy management and growth regulators. In the context of declining land holdings in Telangana, HDPS offers a viable option to increase productivity by 180-300%. This article describes the importance, scope, suitable crops, recommended spacing, varieties, canopy management, nutrient and integrated pest management practices for higher yield under Telangana conditions. Major crops covered are mango, guava, banana, pomegranate, papaya, citrus and dragon fruit.

Keywords: High density planting, canopy management, Telangana, economics, horticulture

Introduction

High Density Planting means planting a greater number of plants than optimum through manipulation of plant architecture. The principle is "More plants per acre, more productive per acre". In India, Dr. B.M. Singh is known as father of HDPS in mango with Amrapali variety. Today, it is widely adopted in Israel, USA, Australia. In traditional horticulture, wider spacing results in low plant population and delayed bearing. For example, mango planted at 10m x 10m accommodates only 40 plants per acre and requires 7-8 years for full canopy development. High Density Planting (HDP) is defined as planting at a density higher than optimum with an objective to achieve early and higher returns per unit area (Bose et al., 2002). The concept was explained by Blackman (1960) based on early interception of solar radiation. In Telangana, where 65% farmers are small and marginal (<2 ha), HDPS is ideal for doubling income from same piece of land.

HDPS is built on four pillars:

(i) Use of dwarf scion varieties
(ii) Use of dwarfing rootstocks
(iii) Scientific training and pruning
(iv) Use of plant growth retardants (Singh, 2018).

Importance, Scope and Economics in Telangana

Telangana has 3.87 lakh hectares under horticulture crops. The average operational holding is 1.12 ha. Therefore, vertical expansion through HDPS is more relevant than horizontal expansion.

Scope in Telangana is high due to:

(a) promotion of drip irrigation under Telangana State Micro Irrigation Project
(b) availability of 50% subsidy under Mission for Integrated Development of Horticulture (MIDH) for HDPS

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(c) proximity to Hyderabad market
(d) suitable red sandy loam soils.

Economic analysis at Fruit Research Station, Sangareddy showed that high density guava (444 plants per acre) recorded net income of Rs. 2.10 lakhs per acre against Rs. 75,000 in conventional planting (Prasad et al., 2021). The payback period in HDPS is 2-3 years compared to 5-6 years in conventional system.



Major Crops, Spacing and Suitable Varieties under HDPS for Telangana

Mango (*Mangifera indica*)

- Spacing: 5m x 3m (270 plants per acre) for semi-dwarf and 3m x 2m (666 plants per acre) for ultra-high density.
- System: Double hedge row and cluster planting.
- Varieties: Amrapali, Mallika, Kesar, dwarf Banganapalli. Rootstocks: Olour, Vellaikulamban for vigour control.
- Suitable districts: Mahabubnagar, Wanaparthy, Nalgonda.
- Canopy management: Central leader removal at 1.0 m height to promote 3-4 primary branches with wide crotch angle. Annual post-harvest pruning during June-July. Maintain tree height at 2.0-2.5 m.
- Growth regulation: Soil application of paclobutrazol @ 3 ml per meter canopy diameter during September induces early and profuse flowering (Burondkar et al., 2013).



Guava *(Psidium guajava)*

Guava is most amenable for HDPS due to its ability to bear on current season growth.



- Spacing: 3m x 3m (444 plants per acre) or Meadow orchard 2m x 1.5m (1333 plants per acre).
- Varieties: Lucknow-49 (Sardar), Allahabad Safeda, Lalit, Arka Amulya. L-49 is widely adopted in Nagarkurnool.
- Nutrient management: Fertigation of 75% RDF - 300:120:200 g NPK plant/year in 10 equal splits.
- Canopy management: Heading back at 60 cm after planting. Coppicing at 30 cm every year in May to regulate winter crop, which fetches premium price.

This is the most suitable crop for HDPS in Telangana due to its bearing on current season growth.

Banana (*Musa spp.)*

- Spacing: Paired row system 1.2 x 1.2 x 2.0m (1600 plants per acre).
- Varieties: Grand Naine (G-9), Dwarf Cavendish.
- Management: Single sucker desuckering, propping, bunch covering



- Fertigation 200:60:200 g NPK/plant.
- Suitable districts: Suryapet, Nalgonda.

Pomegranate *(Punica granatum)*

- Spacing: 3m x 2m (666 plants per acre).
- Varieties: Bhagwa, Super Bhagwa, Arakta.
- Management: Bahar treatment is essential.

Papaya *(Carica papaya)*

- Spacing: 2m x 2m (1000 plants per acre).
- Varieties: Red Lady 786, Arka Prabhath, Pusa Delicious.



Citrus *(Citrus spp.)*

- Sweet orange and acid lime at 4m x 4m (250 plants per acre).
- Varieties: Sathgudi, Balaji.

Dragon Fruit *(Hylocereus spp.)*

- Dragon fruit is a climbing cactus and an emerging high-value fruit in Telangana with market price of Rs. 150-250 per kg.
- Spacing: Concrete pole system, 3m x 2m, 666 poles per acre with 4 plants per pole = 2664 plants per acre (Karunakaran and Arivalagan, 2019).
- Varieties: White pulp - Siam White; Red pulp - Red Jaina, DGF-1; Pink pulp - American Beauty. Red pulp types are preferred for antioxidant content.
- Yield: 6-8 kg per pole in 2nd year and 15-20 kg per pole from 3rd year onwards. Expected yield 8-10 tonnes per acre.
- Suitable districts: Khammam, Mahabubnagar, Rangareddy due to well-drained soils.

Important Operations and Management for Higher Yield

a) Planting material: Use grafted, true-to-type plants from authorized nurseries such as FRS Sangareddy.



b) Canopy management: This is the core of HDPS. Maintain plant height at 2.0-2.5m.
In mango, remove central shoot at 1.0m to develop 3-4 primary branches. In guava, heading back at 60cm and annual coppicing at 30cm during May. In dragon fruit, maintain single stem up to pole top and then allow umbrella-like canopy on RCC ring with 30-40 productive cladodes per pole.



c) Nutrient and water management: Fertigation is mandatory. Apply 75% of recommended dose through drip in 8-10 splits. Mulching with black polythene reduces water loss by 30%. Example: For mango, apply 100:50:100g NPK per plant per year in first year with incremental increase.

d) Use of growth regulators: Paclobutrazol @ 3ml per meter canopy diameter in mango to control vigour and induce flowering (Burondkar et al., 2013). Ethephon and NAA are used in pineapple and mango for flowering and fruit retention.

Integrated Pest and Disease Management (IPDM)

Dense canopy increases humidity.

- **Cultural:** Regular pruning for 30% light penetration.
- **Mechanical:** Yellow sticky traps @ 10 per acre, methyl eugenol fruit fly traps @ 6 per acre.
- **Biological:** Neem Seed Kernel Extract 5%, Trichoderma viride @ 5kg per acre.
- **Chemical need-based:** Imidacloprid for hoppers, copper oxychloride for stem rot in dragon fruit (Wakchaure et al., 2020).

Merits and Demerits

➢ **Merits:**

1. 2.5 to 3.0 times higher yield per unit area.
2. Precocious bearing and early economic returns.
3. Efficient use of water, nutrients and solar radiation.
4. Easy for spraying, pruning and harvesting due to dwarf stature.
5. Better fruit quality and uniformity.

➢ **Demerits:**

1. High initial establishment cost.
2. Requires skilled labour for regular canopy management.
3. If pruning is neglected, overcrowding leads to pest and disease incidence.
4. Requires assured irrigation and fertigation system.

Conclusion

High Density Planting System is a scientifically proven technology for enhancing productivity of horticultural crops. For small and marginal farmers of Telangana, crops like guava, banana, papaya and dragon fruit under HDPS can provide sustainable income of Rs. 2-3 lakhs per acre per year from the second year onwards. Adoption of precise canopy management and fertigation is critical for success.

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ICAR-IIHR'S ARKA VEERA CUCUMBER: CULTIVATING SUCCESS AND EMPOWERING FARMERS

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Improved crop varieties and scientific production techniques can have a significant impact on farmers in the field of vegetable cultivation, where productivity, quality, and effective use of farm resources go hand in hand. In the Bengaluru Rural region, farmers have traditionally been growing solanaceous crops such as tomato, chilli and brinjal repeatedly, following a similar cropping pattern year after year. Over time, this has resulted in nutrient depletion, increased pest and disease problems, greater dependence on plant protection chemicals and declining soil health and productivity. At the same time, growing the same crops in large areas often leads to market glut and price fluctuations, affecting farmers' returns. To overcome these challenges, there is a need to diversify the cropping system by introducing cucurbitaceous crops, which can help break the continuous cropping cycle, reduce pest and disease build-up, minimize market glut and provide farmers with additional crop and income opportunities.

Cucumber (*Cucumis sativus* L.) emerged as a promising option for diversification due to its freshness, nutritional benefits, rapid growth and steady market demand. Among the available improved varieties, Arka Veera, developed by ICAR–Indian Institute of Horticultural Research (IIHR), Bengaluru, offers a suitable choice for farmers as an improved, high-yielding, bitter-free hybrid cucumber variety. Its introduction can help break the continuous solanaceous cropping cycle while providing farmers with an additional crop and income opportunity. It is an early-flowering variety, with the first female flower appearing within 27–34 days. The fruits are green to light green in colour, cylindrical and smooth, and are free from internal core splitting and bitterness. It is tolerant to downy mildew disease and is suitable for round-the-year cultivation. The yield ranges from 25–30 t/ha.

This article highlights the inspiring journey of Mrs. Sushmitha, whose adoption of ICAR-IIHR's Arka Veera cucumber transformed her farming practices, improved her income, and empowered her to make better decisions at the field level.

For smallholder farmers, choosing the right crop variety can make a significant difference to farm income and livelihood security. This was the experience of Mrs. Sushmitha w/o Mr. Madhu**,** a 26-year-old farmer from Ancharahalli village, Bengaluru Rural district. Her family previously earned approximately ₹2.6 lakh per year from conventional crop cultivation; however, fluctuating input costs and unpredictable market conditions frequently affected their income stability. The lack of crop diversification and systematic crop rotation further contributed to declining soil health and increased production risks. Another significant constraint was the heavy dependence on private-sector seeds**,** which substantially increased the cost of cultivation. Despite the availability of cost-effective public-sector varieties, farmers had limited awareness and exposure to these options and lacked sufficient technical guidance and field-level demonstrations to build confidence in their adoption. The absence of regular technical handholding and on-farm support further restricted the adoption and wider dissemination of affordable public-sector seed technologies.

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The introduction of Arka Veera provided her with an affordable and promising opportunity to diversify into vegetable cultivation. With guidance from ICAR-IIHR scientists and training provided under a DST-funded project**,** she cultivated Arka Veera on 0.5 acre**,** adopting improved nutrient and pest management practices. Continuous technical support through group meetings and field demonstrations further strengthened her crop management. The crop gave an early harvest, with uniform, shiny and market-preferred fruits. Its good shelf life enabled her to market the produce without distress and obtain steady returns.







The results were encouraging as use of Ark Veera variety saved 33.33 per cent of seeds expenditure over private variety along with the higher yield. From 0.5 acre, she harvested 11.6 tonnes of cucumber and obtained gross returns of ₹1,97,200 at average price of ₹17/kg**.** Against a cultivation cost of ₹55,000**,** she earned a net profit of ₹ 1,42,200**,** with a B ratio of 3.59. Arka Veera contributed 49.7 per cent of the household income**.** The reusable seed and efficient crop management also resulted in ₹5,000 savings on seed cost**,** ₹6,000–8,000 savings on plant protection and nutrients, and an overall input cost reduction of ₹10,000–12,000**.** The increased income strengthened household financial security, enhanced savings and enabled reinvestment in farm assets. The success of the crop was also linked to its sustainability benefits. The use of Arka Microbial Consortia (AMC), Arka Vegetable Special (AVS) and bio-based pest management inputs like Arka Neem Soap, Arka Pongamia Soap and Arka Cucurlure helped reduce dependence on chemical inputs. The variety's disease tolerance reduced crop-loss risk, while its easier crop management contributed to reduced drudgery for women farmers. Reflecting on her experience, Sushmitha said that Arka Veera gave her the confidence to invest further in vegetable cultivation. Its attractive produce, quick market acceptance and lower seed cost were among the major advantages she appreciated.

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Her success also created interest beyond her own farm. A Field Day organized by the ICAR-IIHR team at her farm during peak crop growth attracted neighbouring farmers and local women SHG members, giving them an opportunity to observe the variety's performance firsthand. Her experience encouraged other farming families to consider affordable public-sector varieties. For Sushmitha, Arka Veera was more than just a cucumber variety it became a pathway to higher income, reduced production costs and greater self-confidence. Her experience demonstrates how the right technology, combined with timely training and continuous technical guidance, can empower farm women, strengthen livelihoods and encourage wider adoption of affordable and sustainable horticultural technologies.

***Source**: ICAR–Indian Institute of Horticultural Research, Bengaluru {DST-funded project titled "Enhancing Livelihood Security of Small-Holder Farm Women of Karnataka through Horticultural Interventions using Pluralistic Extension Approaches" (DST-Viganhara-4305)}*

Conclusion

Arka Veera offered several advantages over costly private hybrids. Being an open-pollinated variety, its seed can be saved and reused, reducing recurring seed expenditure. Its tolerance to downy mildew and suitability for round-the-year cultivation further reduce production risks. The uniform, glossy fruits with good shelf life also received favorable market acceptance. The experiences of farmers presented in the article demonstrate the practical potential of Arka Veera to generate higher returns, reduce recurring seed and crop-management costs, and strengthen household livelihood security.

Overall, wider dissemination of Arka Veera through farmer-to-farmer seed exchange, farmer field demonstrations, FPOs and extension programmes, along with eco-friendly and resource-efficient production practices, can contribute to more profitable, resilient and sustainable cucumber cultivation. Thus, Arka Veera represents not only an improved crop variety but also an opportunity to enhance farmers' income, reduce production risks and promote sustainable horticultural livelihoods.

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IN VITRO & CRYOPRESERVED SEED PHYSIOLOGY AND IN VITRO METHODS FOR REGENERATION AND MULTIPLICATION

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Abstract

Climate change is increasing drought, heat waves and soil salinity, stresses that often strike during germination. Seed priming - pre-treating seeds to give seedlings a head start - is being modernised by combining nanotechnology and artificial intelligence (AI). Nano priming treats seeds with small particles of zinc, silicon, copper, or silver that penetrate the seed coat and activate internal defence and growth mechanisms, such as antioxidant enzymes, resulting in faster, more uniform emergence and stronger roots (Shelar *et al.*, 2021; Bandeppa *et al.*, 2019). Recent field and laboratory trials report improved germination percentage, seedling vigour and drought resistance in nanoprimed pea, wheat and tomato seeds compared with untreated seeds (Pavlović *et al.*, 2024). AI-powered imaging and machine learning are also being combined with seed handling: high-resolution cameras and algorithms now predict viability, vigour and nanoparticle dosage in real time, replacing slow manual grading (Rani *et al.*, 2021). Bio-based, plant-extract-synthesised ("green") nanoparticles are emerging as a less toxic alternative to chemically synthesised ones, easing environmental concerns (Aggarwal *et al.*, 2025). Challenges remain, including variable crop responses, limited long-term safety data, and scale-up of AI-driven sorting in commercial seed companies (Gohari *et al.*, 2025). Even so, AI-integrated nanopriming is one of the most promising routes toward more resilient food production on increasingly unpredictable land.

Introduction

Plant genetic resources are conserved ex situ, through seed banks, field genebanks and in vitro/cryo banks, or in situ, in natural habitats and on-farm systems. Conventional seed banking is the cheapest and most widely used ex situ strategy, but it works only for species whose seeds tolerate desiccation (Roberts, 1973). Many tropical, forest and vegetatively propagated crop species produce seeds that are damaged by drying, or are propagated clonally and cannot be conserved as true seed at all; for these, plant tissue culture and cryopreservation, combined with in vitro regeneration and multiplication, are the only realistic means of long-term conservation, sanitation, mass propagation and international exchange of germplasm (Engelmann, 2004). This report examines two linked bodies of technology: first, the physiology of seed and embryo tissue under in vitro and cryogenic conditions, and the biophysical basis of desiccation and freezing tolerance; second, the in vitro methods - organogenesis, somatic embryogenesis, micropropagation and synthetic seed technology - used to regenerate and multiply plants once material has been rescued, conserved or improved in culture. Case studies from the primary literature are used throughout to ground the discussion in real conservation and production programmes.

In Vitro and Cryopreserved Seed Physiology

1. Seed Storage Categories: Orthodox, Recalcitrant and Intermediate

Roberts (1973) first classified seeds by storage behaviour. Orthodox seeds acquire desiccation tolerance during late maturation, can be dried to low moisture content (often below 5%) and stored

at sub-zero temperatures for years to decades. Recalcitrant seeds are shed at high moisture content (commonly 30-50%), never acquire drying tolerance, are often chilling-sensitive, and remain viable for only weeks to a few months even under the best ex situ conditions. A third, intermediate category was later defined using coffee as the model: intermediate seeds tolerate drying to lower moisture than recalcitrant seeds but are progressively injured by sub-zero or even chilling temperatures once dried, so conventional genebank protocols are only partially effective (Ellis *et al.*, 1990). Economically important recalcitrant or intermediate species include cocoa, coconut, rubber, mango, jackfruit, many Citrus species, tea, oil palm and numerous rainforest trees - a major reason their ex situ conservation depends on in vitro and cryogenic methods rather than dry seed banking.

Table 1. Comparison of Seed Storage Physiological Categories

Feature	Orthodox	Intermediate	Recalcitrant
Desiccation tolerance	High (survives <5% moisture)	Moderate (~7-10% MC)	Low/absent (damaged 20-50% MC)
Optimal storage temp.	Sub-zero (e.g. -18°C)	Chilling-sensitive, above freezing	Warm, moist; freezing lethal
Typical ex situ longevity	Years to decades	Months to a few years	Days to a few months
Representative species	Cereals, most legumes, many vegetables	Coffee, Citrus, tea, oil palm	Cocoa, coconut, mango, jackfruit, rubber
Conservation strategy	Conventional dry/cold seed bank	Short-term cold storage; in vitro/cryo back-up	Field genebank, in vitro culture, cryopreservation

2. Physiological and Molecular Basis of Desiccation Tolerance

Desiccation tolerance is acquired during mid- to late seed maturation through several coordinated mechanisms: accumulation of non-reducing sugars that vitrify the cytoplasm into a stable glassy state at low water content; synthesis of late embryogenesis abundant (LEA) proteins that stabilise membranes and macromolecules during water loss; induction of antioxidant systems that limit oxidative damage as metabolism slows; and a general metabolic "switch-off" with dedifferentiation of organelles that reduces reactive oxygen species (ROS) as water potential falls. Recalcitrant legume seeds possess far fewer LEA proteins and fail to execute the ABA/ABI3-regulated late maturation programme that orthodox seeds undergo, explaining their desiccation sensitivity (Delahaie *et al.*, 2013). In intermediate seeds such as coffee, the same transcriptional switch - repressing primary metabolism, photosynthesis and respiration while inducing LEA proteins, heat-shock proteins and antioxidant enzymes - runs only partially, explaining coffee's partial, temperature-dependent tolerance. Practically, orthodox seeds tolerate drying below roughly 0.07 g H2O per g dry weight, recalcitrant seeds are injured above roughly 0.2 g H2O per g dry weight, and intermediate types fall in between. Because recalcitrant and intermediate seeds cannot simply be dried and frozen, in vitro culture of excised embryos or embryonic axes, and ultimately cryopreservation of those explants, has become the principal route for conserving their genetic diversity.

3. In Vitro Culture of Seeds, Embryos and Embryonic Axes

In vitro seed physiology begins with aseptic culture: mature or immature zygotic embryos, embryonic axes or whole seeds are surface-sterilised and cultured on defined media to bypass germination barriers, rescue hybrid embryos that abort in vivo, or multiply scarce, dormant or short-lived seed material. This is essential for orchids, whose minute, endosperm-free seeds germinate poorly without a fungal symbiont or an external nutrient source (asymbiotic culture); for embryo rescue in wide interspecific crosses; and for recalcitrant-seeded species, where the embryonic axis rather than the whole seed is excised to escape the desiccation and chilling sensitivity of surrounding tissue. Once established, seed-derived cultures can be multiplied under normal conditions or placed under slow-growth conditions to extend subculture intervals for medium-term genebanking. However, slow-growth maintenance is suitable only for a limited period, given the cumulative risk of somaclonal variation, contamination and labour cost - which is why cryopreservation is favoured for true long-term storage of in vitro-derived germplasm.

Cryopreservation of Seeds and Plant Germplasm

1. Principles of Plant Cryopreservation

Cryopreservation stores living material in or above liquid nitrogen (LN, typically -196°C), where diffusion-dependent reactions are essentially arrested, permitting theoretically indefinite storage with minimal genetic drift (Engelmann, 2004). It has been applied to orthodox and non-orthodox seeds, pollen, dormant buds, in vitro shoot tips and axillary buds, embryogenic and non-embryogenic cell cultures, protoplasts and embryonic axes; an in vitro culture system is usually a prerequisite for regenerating and multiplying cryopreserved propagules, although some routes (e.g. direct germination of cryopreserved seeds, micro-grafting of recovered buds) minimise or bypass this step. The central technical challenge is preventing lethal intracellular ice. All modern methods therefore dehydrate tissue - physically (drying) or osmotically (concentrated cryoprotectant solutions) - before LN plunge, so remaining cellular water solidifies as an amorphous glass rather than damaging ice. Cryopreservation nonetheless imposes substantial osmotic, chemical and cold stress, reliably inducing oxidative stress (ROS accumulation, lipid peroxidation) and sometimes leaving a transient epigenetic signature, including altered DNA methylation, in surviving tissue.

2. Major Cryopreservation Techniques

Slow (controlled-rate) freezing: cryoprotected explants are cooled slowly (~0.5-2°C/min) to an intermediate temperature (roughly -35 to -40°C) for controlled extracellular ice formation and progressive dehydration, before LN plunge. Among the earliest methods, it remains useful for suspension and embryogenic cell cultures but is equipment-heavy and slow for genebank-scale operation.

Vitrification (PVS): highly concentrated, multi-component cryoprotectant solutions - most famously Plant Vitrification Solution 2 (PVS2), developed by Sakai, Kobayashi and Oiyama (1990) for citrus nucellar cells - osmotically dehydrate tissue before rapid, direct LN immersion. Because remaining water solidifies as glass rather than ice, vitrification avoids many slow-freezing injuries and is now the most widely applied approach for shoot tips, embryogenic tissue and embryonic axes.

Encapsulation-dehydration and droplet-vitrification: encapsulation-dehydration embeds explants (often somatic embryos or shoot tips) in calcium-alginate beads that are osmotically pre-cultured, air-dried and frozen, with the alginate coat protecting tissue mechanically. Droplet-vitrification combines PVS2/PVS3 dehydration with placing the explant in a small droplet of vitrification solution

on foil, plunged directly into LN; the droplet's high surface-area-to-volume ratio gives very rapid cooling/warming, improving survival for many recalcitrant-to-cryopreserve species. First generalised across the entire banana family (Musaceae), it is now one of the most broadly "generic" plant cryopreservation methods, and has since extended to potato, strawberry, garlic, mint, shallot and other vegetatively propagated and medicinal species (Panis, Piette & Swennen, 2005).

Table 2. Overview of Principal Plant Cryopreservation Methods

Method	Basic Principle	Typical Material	Notable Strength
Slow freezing	Controlled-rate cooling to ~-35 to -40°C before LN plunge	Cell/embryogenic suspensions	Well suited to fine cell cultures
Vitrification (PVS2/PVS3)	Osmotic dehydration in concentrated cryoprotectant, then direct LN plunge	Shoot tips, embryonic axes	Broadly applicable; avoids ice formation
Encapsulation-dehydration	Alginate-bead encapsulation, air-drying, then LN	Shoot tips, somatic embryos	Mechanical protection; simple handling
Droplet-vitrification	PVS-treated tissue frozen in a droplet on foil for rapid heat transfer	Meristems, shoot tips (banana, potato)	Very high cooling/warming rates; near-generic

3. Post-Cryopreservation Regrowth and Genetic Stability

Surviving the freezing step is only half of a successful protocol; recovery-stage conditions are equally critical. Popova, Kulichenko and Kim (2023) reviewed five strategies to improve post-cryopreservation regrowth: adjusting recovery-medium mineral composition (e.g. removing iron and ammonium, which can catalyse oxidative damage); exogenous antioxidant or adsorbent additives to counter oxidative stress and residual cryoprotectant toxicity; manipulation of medium osmotic potential; control of light/dark conditions and light quality; and careful selection of growth regulators appropriate to the tissue. Genebanks typically require a post-thaw regeneration rate of at least ~35% before adopting a protocol for routine banking (Popova *et al.*, 2023). Genetic fidelity is validated with phenotypic and molecular markers (e.g. SSR profiling): cryopreserved banana meristems have regenerated plants with SSR similarity coefficients above 0.9 relative to untreated controls, with statistically comparable growth and yield after field establishment, supporting genetic stability when protocols are properly optimised (Van den Houwe *et al.*, 2020).

Case Studies I

1. The International Musa Germplasm Transit Centre (ITC) Banana Cryobank

Banana and plantain (*Musa* spp.) are vegetatively propagated, and many accessions are seedless or recalcitrant-seeded, ruling out conventional seed banking. The CGIAR genebank's ITC, hosted by Bioversity International (now the Alliance of Bioversity International and CIAT) in Belgium, maintains an in vitro collection of over 1,600 banana accessions from 38 countries, backed up by cryopreservation; over 35+ years it has distributed more than 18,000 accession samples to researchers and farmers in 113 countries under the International Treaty on Plant Genetic Resources for Food and Agriculture (Van den Houwe *et al.*, 2020). Its droplet-vitrification protocol - cold-

hardening of donor material, sucrose pre-culture, PVS2 osmotic dehydration, and ultra-rapid freezing of the meristem in a droplet - is regarded as the first broadly generic cryopreservation protocol for plant tissues and has since been adapted to shoot cultures and somatic embryos of other species (Panis *et al.*, 2005; Van den Houwe *et al.*, 2020). Comparative studies show that even field-collected sucker meristems, not only laboratory-raised shoot cultures, can be cryopreserved successfully by droplet-vitrification, with post-thaw regeneration of ~60%, comparable to conventional in vitro explants, while shortening preparation time from 8-14 months to roughly two.

2. Cryopreservation of Threatened Medicinal Plant Germplasm

Beyond major crops, cryopreservation and in vitro slow-growth genebanking safeguard threatened or medicinally important species with limited or non-orthodox seed production. *Gentiana kurroo*, a critically endangered Himalayan medicinal herb, is conserved as slow-growing in vitro cultures at India's National Bureau of Plant Genetic Resources; excised shoot tips are cold-hardened, pre-cultured with dimethyl sulfoxide, dehydrated in PVS2, and cryopreserved by both conventional vitrification and droplet-vitrification - the latter achieving markedly higher post-thaw regeneration (~60%) than conventional vitrification (~35%) across accessions tested. This exemplifies how cryopreservation protocols must typically be fine-tuned per species, or even genotype, before routine adoption.

In Vitro Methods for Regeneration and Multiplication

1. Micropropagation

Micropropagation is the clonal, aseptic multiplication of plants in vitro, producing large numbers of genetically uniform, disease-free plantlets from a small amount of elite material, including material rescued from recalcitrant seeds or recovered from cryopreservation. The workflow has four stages: Establishment (introducing a sterilised explant to an appropriate medium); Multiplication (repeated subculture on a medium, typically containing a cytokinin such as 6-benzylaminopurine, that promotes shoot proliferation); Rooting (transfer to an auxin-containing medium to induce roots); and Acclimatisation/hardening-off (gradual transition from the humid, heterotrophic in vitro environment to normal ex vitro conditions) (Bhardwaj *et al.*, 2025). Culture media are almost universally based on the mineral salts of Murashige and Skoog (1962). Recent advances include temporary immersion bioreactor systems that periodically flood and drain explants to improve gas exchange and reduce hyper-hydricity; LED lighting tuned to improve photoautotrophic growth; and molecular diagnostics integrated into micropropagation pipelines to screen for pathogens and confirm trueness-to-type - all improving efficiency, scalability and commercial feasibility (Bhardwaj *et al.*, 2025).

2. Organogenesis

Organogenesis is the de novo formation of unipolar organs from explant tissue, typically via an intervening callus phase (indirect organogenesis) or directly from explant cells (direct organogenesis). It is fundamentally regulated by the auxin:cytokinin balance in the medium: high cytokinin-to-auxin ratios favour shoot formation, while high auxin-to-cytokinin ratios favour root formation. Long, Yang, Pan and Shen (2022) reviewed the molecular control of de novo shoot and root organogenesis, showing that pluripotent callus formation and organ specification are governed by overlapping transcription-factor networks, auxin/cytokinin signalling crosstalk, and epigenetic reprogramming of explant tissue, giving mechanistic grounding to these long-used empirical hormone-ratio rules.

3. Somatic Embryogenesis

Somatic embryogenesis is the process by which somatic (non-reproductive) cells, usually induced by an auxin such as 2,4-dichlorophenoxyacetic acid, develop into bipolar embryo-like structures with both apical (shoot) and basal (root) meristems, allowing plantlet formation without an organogenic step. Somatic embryos are of particular interest as the biological basis of synthetic seed technology, an efficient route to mass clonal propagation of elite genotypes, and amenable to cryopreservation for long-term conservation of clonal or recalcitrant-seeded germplasm (Long *et al.*, 2022). Somatic embryogenesis also underpins virus elimination, ploidy manipulation, genetic transformation, and - combined with temporary immersion bioreactors - large-scale automated propagation of species such as Arabica coffee.

4. Synthetic Seed (Synseed) Technology

Synthetic seeds are somatic embryos, or other regenerable micropropagules such as axillary buds, shoot tips or nodal segments, individually encapsulated in a protective, nutrient-supplemented gel matrix so they can be handled, stored, transported and sown like a botanical seed (Redenbaugh *et al.*, 1986). Sodium alginate gelled with calcium chloride is the preferred matrix, owing to low toxicity, appropriate mechanical strength, low cost and ease of gelation; typical protocols use 2-6% sodium alginate solidified in 75-100 mM calcium chloride, often supplemented with growth regulators, chelated iron and antimicrobial agents (Ghosh *et al.*, 2026). Synthetic seeds are classified as desiccated (partially dried, for short- to medium-term ambient storage or exchange) or hydrated (kept moist, typically refrigerated, for shorter-term storage or immediate propagation). Documented applications span tomato, sweet potato, cauliflower, broccoli, cassava, sweet pepper, asparagus, cucumber, carrot, eggplant and potato among vegetables (Ghosh *et al.*, 2026), as well as tree, ornamental and medicinal species - particularly valuable for seedless (parthenocarpic) crops and species with recalcitrant true seed.

Case Studies II

1. Encapsulated Somatic Embryos in Date Palm and Citrus

In date palm (*Phoenix dactylifera*), an economically vital but slow-multiplying tree traditionally propagated via offshoots, somatic embryos are encapsulated in sodium alginate to create synthetic seeds for propagation, storage and international exchange. Comparative testing found 3% sodium alginate dropped into 2.5% calcium chloride solution gave the best gel-matrix performance for embryo maintenance and post-storage recovery, storage at 5°C improved survival, and supplementing the conversion medium with 20 g/L sucrose enhanced plantlet conversion. In Citrus, encapsulation of somatic embryos in nutrient-enriched calcium-alginate gel similarly protects embryos from mechanical damage during handling and transport while supporting development into plantlets, offering an efficient alternative to conventional nucellar or zygotic propagation for elite or pathogen-tested clones.

2. Asymbiotic Seed Culture and Micropropagation of Endangered Orchids

Orchidaceae, with roughly 28,000 species, constitutes about 8% of angiosperm diversity, yet many orchid species are now endangered by habitat loss, climate change and overcollection. Orchid seeds are minute, essentially endosperm-free, and depend in nature on symbiotic mycorrhizal fungi for germination, so in vitro asymbiotic culture has become a key conservation and propagation tool. Park *et al.* (2023) developed an asymbiotic germination protocol for the critically restricted terrestrial orchid Cypripedium guttatum, showing that surface sterilisation with 1% sodium

hypochlorite combined with dark incubation improved germination, and that the auxin naphthaleneacetic acid (NAA) further enhanced protocorm formation, while organic supplements such as apple and banana homogenate substantially inhibited long-term seedling growth - underscoring the need for species-specific optimisation even within a single genus. Similar asymbiotic protocols conserve other threatened orchids, including the Siberian terrestrial orchid Orchis militaris, where matching in vitro conditions to the species' natural seasonal temperature and photoperiod cycle improved seedling survival, and the Korean epiphytic orchid Pelatantheria scolopendrifolia, for which half-strength Murashige and Skoog medium supported germination and root/shoot formation in about 70% of seeds within twelve weeks. These studies show how in vitro seed culture can both rescue reproduction in poorly germinating species and generate plantlets for habitat restoration and ex situ conservation.

Applications and Significance

- Ex situ conservation of genetic diversity in species that cannot be banked as dry seed, including many tropical trees, vegetatively propagated crops and medicinal plants.
- International exchange of pathogen-tested planting material, exemplified by the ITC banana genebank's distribution of clean germplasm to over 100 countries.
- Mass clonal multiplication of elite, disease-free or genetically improved planting stock for horticultural and forestry industries.
- Rescue and propagation of rare, threatened or slow-reproducing species (e.g. terrestrial orchids) for habitat restoration and reintroduction.
- Production, storage and low-cost distribution of true-to-type propagules via synthetic seed technology, particularly for seedless or recalcitrant-seeded crops.
- Provision of standardised, pathogen-free explants for downstream biotechnological applications such as genetic transformation, secondary metabolite production and cryobanking of transgenic lines.

Challenges and Future Directions

Cryopreservation protocols are frequently genotype- and even accession-specific: a technique that gives excellent post-thaw regrowth in one Musa or Citrus accession may perform poorly in a related wild relative, requiring costly, iterative optimisation before routine genebank adoption (Van den Houwe *et al.*, 2020). The cumulative physical, osmotic and oxidative stresses of cryoprotectant exposure and ultra-rapid cooling can induce epigenetic changes and, in some genotypes, somaclonal variation, motivating ongoing molecular studies to identify stress-tolerance markers and refine protocols. In vitro slow-growth genebanking, while a useful medium-term backup, is not suited to indefinite storage given accumulating contamination/variation risk and recurring labour and consumable costs, reinforcing cryopreservation as the preferred long-term solution once a workable protocol exists. Cost-effective scale-up of micropropagation and synthetic seed systems for commercial deployment remains constrained by labour-intensive manual handling, motivating work on temporary immersion bioreactors, automation and simplified low-cost culture systems (Bhardwaj *et al.*, 2025). Future priorities highlighted across the literature include wider application of "generic" droplet-vitrification-type protocols across related plant families to reduce de novo optimisation; transcriptomic and proteomic profiling to rationally design recovery-stage media rather than relying on empirical trial and error (Popova *et al.*, 2023); greater routine use of molecular fidelity testing (e.g. SSR markers) after cryopreservation and long-term in vitro culture; and continued development of synthetic seed technology, including AI-assisted optimisation of

encapsulation formulations, to extend clonal, storable propagules to a wider range of crops and threatened species.

Conclusion

In vitro and cryopreservation technologies have transformed the conservation and multiplication of plant genetic resources that fall outside the scope of conventional dry seed banking. A clear understanding of seed physiological categories - orthodox, intermediate and recalcitrant - explains why particular species require these specialised approaches, while advances in cryoprotection chemistry (vitrification solutions), physical technique (droplet-vitrification, encapsulation-dehydration) and post-thaw recovery science have made ultra-low-temperature storage a practical, scalable option for an increasingly wide taxonomic range, as demonstrated by large operational gene banks such as the ITC banana collection. In parallel, organogenesis, somatic embryogenesis, micropropagation and synthetic seed technology provide the complementary toolkit needed to regenerate, multiply and distribute this conserved germplasm as usable planting material. Continued refinement of these interlinked technologies, guided by molecular insight into desiccation and cryo-tolerance mechanisms, will be essential to safeguarding global plant biodiversity and supporting sustainable agriculture and horticulture in the decades ahead.

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THE INDIAN AQUASCAPING RENAISSANCE

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Introduction

Aquascaping is derived from the Latin word “aqua” means water with the English word “landscaping”. It is the art and craft of arranging aquatic plants, rocks, stones, driftwood and substrates inside an aquarium to create a visually appealing natural landscape. It is often described as “Gardening underwater", it shifts the focus of traditional fish keeping from just keeping fish alive to designing a living balanced and artistic miniature ecosystem that mimics natural landscapers like forests, mountains or riverbanks. It's a popular hobby among fish keepers as it allows them to create an aesthetically pleasing and natural looking environment for their aquatic pets.

History

Aquascaping has its roots in the Netherlands During 1930's. Dutch hobbyists started creating beautiful aquariums by arranging different aquatic plants in a planned way. This became known as the Dutch style. It mainly focused on plant arrangement, colour, size and creating a sense of depth, Dutch style gave more importance to plants and their beauty.



(Source :Aquarium lesson, Dutch style aquarium).

The modern form of aquascaping was greatly influenced by the Japanese aquascaper Takashi Amano, introduced nature aquarium Concept in 1990's. He used plants, rocks, driftwood to recreate natural scenes as forests, rivers and mountains inside the aquarium. The Dutch organised plants like a formal garden, Amano organised plants like a forest.



(Source: Aquarium architecture, legendary aquarist Takashi Amano)

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The Rise of aquascaping in India:

Over the past decade, aquascaping in India has grown from a small hobby into a rapidly developing creative field. It was once, limited to a few enthusiastic but now attracted a growing community of hobbyists, artists and professionals across the country. Indian aquascapers such as AdipSajjan Raj, Rahul Mukherjee and Durveshgaikar have gained recognition for their creative layouts and careful plant arrangement. Their work has helped bring greater visibility to Indian aquascaping and has encouraged more enthusiasts to explore this art more. Indian aquascaping continues to develop its own identity. From small home aquariums to Competition level display shows that India is developing a vibrant and creative aquascaping culture (Mukherjee *et al*., 2012).

Science behind the beauty

An aquascape may look like a beautiful underwater painting, but behind that beauty is a carefully balanced miniature ecosystem. Plants are the heart of an aquascape, and different species have different shapes, growth rates and environmental requirements. Choosing plants according to their size and growth pattern helps create depth and a natural appearance. Foreground plants such as *Glossostigma* and *Eleocharis* can form carpets, while *Cryptocoryne, Anubias* and Java fern provide structure. *Hydrocotyle tripartita* is also popular for creating dense, natural-looking growth.

Light is the engine of an underwater garden. Plants use light for photosynthesis, the process through which they produce energy and release oxygen. The intensity and duration of light should match the plants being grown. Low-light plants such as *Anubias* and Java fern require less intense lighting, while demanding carpeting plants need stronger light. A controlled photoperiod of around 6–9 hours per day is commonly used, with adjustments based on plant growth and algae levels. Too little light can weaken growth, while excessive light without sufficient CO_2 and nutrients can encourage algae.

CO_2 and nutrients provide the resources plants need to grow. Dissolved CO_2 acts as a carbon source for photosynthesis, and controlled CO_2 injection can improve the growth of demanding plants, particularly carpeting species. Many high-tech planted aquariums operate around 20– 30 ppm. Plants also require macronutrients such as nitrogen, phosphorus and potassium, along with micronutrients such as iron and other trace elements. Maintaining a balance between light, CO_2 and nutrients is essential because excess light or nutrients can contribute to algae problems (Tropica Aquarium Plants, 2026).

Finally, water quality connects the entire system. Temperature, pH, ammonia, nitrite and nitrate influence the health of plants, fish and beneficial microorganisms. Microorganisms break down organic waste and help convert harmful compounds into forms that plants can use. Therefore, the beauty of an aquascape is not created by decoration alone—it comes from understanding how plants, light, CO_2, nutrients, water and living organisms work together. Aquascaping is ultimately the art of creating beauty through the science of a living aquatic ecosystem. (Tropica Aquarium Plants, 2026).

Regional styles in India

The global aquascaping community recognizes standard foundational designs like Japanese, Iwagumi, European, Dutch. India has developed a distinct regional landscape for the hobby. The regional styles of aquascaping in India are primarily driven by the Local availability of unique river landscapes native plant species, regional climatic adaptations.

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1) Western Ghats and Northeast biotopes (Ecological styles)

Driven by a strong push toward ecological authenticity, this style focuses on replicating native river ecosystems of India. The fast-flowing clear water streams of western Ghats of Kerala, Karnataka or shaded forest streams of north-east India of Assam, Meghalaya. key materials include fine river sand, natural smooth river pebbles, native botanicals like Indian almond leaves (mulberry) to create clear water stream beds. Flora & Faunas includes native plants like *Hygrophila pinnatifida, Rotala* with regional fishes like Denison barbs (miss Kerala).



(**Source:** Biotope Aquarium – Small stream in Tamil Nadu state, Western Ghats, India.)

2) The western India" Monsoon Jungle" style

Highly popular in high humidity coastal hubs like Mumbai, Pune, goa adapts the global Jungle style into a localized representation of India's dense monsoon forests. It is highly favored by beginners because it is incredibly forgiving and thrives in low-tech setups. Key materials include branching local driftwood and heavy forest stones flora include low maintenance plants like Java fern, *Anubias* are used.



(Source: Biotope Aquarium.)

3) Himalayan diorama style:

Prominent in northern aquascaping hubs, it is a theatrical style that uses forced perspective to create miniature landscapes. The rugged, towering cliff faces, deep valleys, winding roads of Himalayas are the regional inspiration. flora includes micro scale plants like, *micranthemum monte caulo* used to resemble distant grass plains.



(Source: Aquatic Gardeners Association (AGA) Aquascaping Contest – Mount Nandadevi view from my balcony, by Dr. Kaushik Bose, India.)

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4)The desi Dutch street style:

A localized adaptation of the traditional European Dutch style. Because high quality hardscape can be expensive many hobbyists opt for an entirely plant focused layout. The design relies entirely on contrasting colors, textures, heights of different plant groupings arranged in streets. *Rotala rotundifolia, ludivigia repens, alternanthera reineckii*are the flora's used to make desi Dutch street style.



(Source: Aquatic Gardeners Association (AGA) Aquascaping Contest – The Royal Bengal Aqua Garden, Dutch-style aquascape.)

High tech aquascaping innovation:

Technology has changed aquascaping from a simple hobby into a more precise and controlled form of underwater gardening. Advanced LED lighting is the one of the major innovations, it allows users to adjust brightness, color and intensity so the plants receive right amount of light for photosynthesis, making the colors more attractive. co2 injection system is another important development. Controlled co2 Supply can improve plant growth and help aquascapers grow Demanding aquatic plants, co_2 can produce more healthy plant growth. Modern filtration systems help keep water clean by removing waste and circulating water throughout the aquarium (Sutedja *et al*., 2023).

Specialised fertilizers provide essential nutrients as nitrogen, phosphorus, potassium, help aquascapers meet specific needs of different plants, Digital timers, automatic dosing system, temperature controllers and water quality Sensors can monitor and manage Important aquarium conditions with less manual effort.



(Source:CO2Art,High-tech aquascaping system integrating LED lighting, CO_2 injection and filtration.)

Government schemes and financial support for aquascaping in India

Aquascaping may begin as a hobby, also open doors to ornamental fish farming, aquarium businesses and entrepreneurship, thus it receives government attention, creating opportunities for people. One of major initiatives is Pradhan Mantri Matsya Sampada Yojana, include Support for ornamental fisheries, covering ornamental fish rearing, breeding, integrated production units.

PMMSY provide backyard ornamental fish rearing units costing around 3 lakh rupees, about rupees 1.20 lakh for general beneficiaries, 71.80 lakh for women and Sc/ST beneficiaries. An integrated ornamental fish unit has indicative Cost of rupees 25 lakh, and integrated marine ornamental fish unit of rupees 30 lakh (Department of Fisheries, Government of India ,2020). The growth of the sector is also visible in Tamil Nadu, where Madurai has been identified as an ornamental fisheries cluster.

Aquascaping trade in India

India's aquascaping trade is gradually developing from a hobby-based activity into a specialized ornamental aquarium business. The trade is not limited to ornamental fish, it includes aquatic plants, aquarium tanks, Substrates, rocks, driftwood, lighting, filters, Co2 equipment, fertilizers & other accessories. A major feature of the Indian market is its dependence on imported aquascaping equipment, specialized accessories. This creates opportunities for Indian entrepreneurs to develop locally produced equipment, plant nurseries (Mukherjee, M. *et al*,2012).

The trade also benefits from India’s rich diversity of ornamental fishes and aquatic plants with proper breeding, cultivation, marketing. India's aquascaping trade is evolving from selling fish to selling complete underwater ecosystems. India is no longer just watching aquascaping scene. In the 2025 IAPLC, 66 entries came from India, placing Indian aquascapers among participants from 77 countries and regions (Mukherjee, M. *et al*,2012).

India on global aquascaping stage

Indian aquascapers are now taking part in international competitions such as International aquatic plants layout contest (IAPLC) provide a platform for aquascapers. India has also developed its own competitive platform through great Indian aquascaping contest give Indian aquascapers a chance to improve their skills & gain wider recognition. Success in aquascaping requires knowledge of plants, lights, co2, nutrients, water quality, ecology at same time aquascapers need creativity to arrange rocks, wood and plants to create a natural appearance. Globally, Japan, China, Malaysia are the countries with strong aquascaping communities. In India, west Bengal, Tamil Nadu, Kerala, Maharashtra are important Centers of wider ornamental fish & aquarium Sector that supports the growth of aquascaping (Aqua Design Amano, 2025).

The future of smart and sustainable aquascaping

The future of aquascaping is moving towards smarter and more sustainable aquariums. Water quality sensors can monitor conditions such as temperature, ph., water parameter. Smart lighting Systems automatically control light intensity and timing, reduce electricity use. Automatic CO2 and fertilizer systems can deliver controlled amounts when needed, reduce the waste of co2 and nutrients. Smart temperature Controllers can maintain a suitable temperature without constantly running heating or cooling equipment. However smart technology itself should be used responsibly. The future of aquascaping is not simply smarter technology, it is smarter use of technology in harmony with nature.

Conclusion

Aquascaping in India is growing from a simple aquarium hobby into a creative and developing field that brings together art, science, technology and entrepreneurship. From natural landscapes and carefully selected plants to smart equipment and sustainable practices, Indian aquascapers are creating their own identity while connecting with the global aquascaping community. The future of Indian aquascaping is about creating healthy ecosystems, developing local businesses, using technology wisely and reducing unnecessary use of resources. From a hobby in a glass tank to a growing underwater movement, the Indian aquascaping renaissance is just beginning.

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THE INDIAN BLUEBERRY REVOLUTION: A STORY OF SCIENCE, INNOVATION, AND OPPORTUNITY

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Abstract
Blueberry cultivation in India has evolved from a little-known fruit crop two decades ago into an emerging high-value horticultural industry. The introduction of commercially viable highbush blueberry cultivars has created new opportunities for domestic production across diverse agroclimatic regions. At present, approximately 725 hectares are under blueberry cultivation, producing nearly 5,000–6,000 metric tons annually. However, domestic production remains insufficient to meet growing consumer demand, with annual imports exceeding 20,000 metric tons. Advances in cultivar development, micropropagation, protected cultivation, and sustainable farming practices are supporting the expansion of blueberry production. This growing industry reflects India's progress in horticultural innovation, agricultural entrepreneurship, and efforts to reduce dependence on imported fruit.

Keywords: Blueberry, cultivation, propagation, tissue culture, India

Introduction

Twenty years ago, blueberry plants were virtually unknown in India. They appeared only in imported punnets displayed on the shelves of luxury supermarkets and were regarded more as an exotic curiosity than a fruit that could be cultivated in Indian fields. Their imported origin and high market price made them inaccessible to most consumers, while farmers considered blueberry cultivation impractical under Indian conditions. Little did anyone know that this small berry would eventually emerge as one of the country's most promising high-value horticultural crops. The journey began with a small but significant step when scientists at the Department of Horticulture, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya (CSKHPKV), Palampur, initiated the first systematic trials on blueberry cultivation during 2007–08. Although these were small-scale experiments, they marked the beginning of an agricultural revolution whose impact continues to expand today, laying the scientific foundation for India's emerging blueberry industry (Rana *et al*., 2020).

During the initial phase, most of the cultivars introduced into India belonged to the Rabbiteye blueberry (*Vaccinium ashei*), a species recognised for its adaptability in several parts of the world. Their introduction generated considerable enthusiasm among researchers and growers, who visualized the establishment of a profitable new fruit industry. However, field evaluations soon revealed several practical limitations. The plants produced comparatively poor yields, required labour-intensive harvesting procedure, and failed to perform consistently across India's diverse

agroclimatic conditions. These findings demonstrated that simply introducing foreign cultivars would not be sufficient to establish a sustainable blueberry industry. Instead, India required cultivars capable of adapting to different climatic zones while supporting modern production technologies for commercial cultivation (Negi, 2025).

While India was still evaluating the prospects of blueberry cultivation, the fruit had already become a global agricultural success story. Countries such as the United States, Canada, Chile, Peru, and several European nations had successfully established blueberries as an important commercial crop. Beyond their pleasant flavour, blueberries gained worldwide recognition because of their exceptional nutritional value. They are regarded as a "superfruit", rich in anthocyanins, flavonoids, vitamin C, dietary fibre, and powerful antioxidants. Regular consumption has been associated with improved cardiovascular health, enhanced immunity, better cognitive function, diabetes management, reduced oxidative stress, and healthy ageing. This growing global popularity also increased consumer demand in India, leading to annual imports exceeding 20,000 metric tons, clearly indicating that domestic production was unable to satisfy the rapidly expanding market (Medicon, 2025).

The substantial demand–supply gap encouraged Indian researchers to identify cultivars better suited to local agroclimatic conditions. Most parts of India were unsuitable for traditional high-chill cultivars such as Duke and Legacy, which require prolonged winter chilling for optimum growth and fruiting. A major breakthrough came with the introduction of Southern Highbush blueberries, followed by low-chill and zero-chill cultivars such as Biloxi and Cupla. These improved cultivars required significantly fewer chilling hours and successfully adapted to warmer climates, allowing blueberry cultivation to expand beyond the Himalayan region into states such as Maharashtra, Karnataka, Tamil Nadu, and Telangana. This remarkable advancement transformed blueberries from an experimental crop into a commercially viable horticultural enterprise across diverse Indian landscapes (Tanisha *et al*., 2026).

Current Scenario

The real breakthrough in India's blueberry revolution came with the development of commercially viable cultivars such as highbush blueberry (*Vaccinium corymbosum*) by the CSIR–Institute of Himalayan Bioresource Technology (CSIR-IHBT), Palampur. These cultivars not only produced superior fruit quality but also exhibited higher productivity and greater adaptability to Indian growing conditions, providing farmers with practical alternatives to the previously introduced Rabbiteye cultivars. Beyond developing improved cultivars, ongoing research is focused on optimising efficient plant tissue culture and agricultural techniques for blueberry. Current efforts aim to establish and refine protocols for elite cultivars, facilitating the rapid multiplication of disease-free, genetically uniform planting material and high nutritional fruits. These ongoing studies are expected to reduce dependence on expensive imported planting material and support the future establishment of commercial blueberry orchards across India (Abhilash Padhan et al., 2025).

One of the most transformative developments was the adoption of plant tissue culture for large-scale propagation. Traditional propagation method through stem cuttings could not meet the rapidly increasing demand for quality planting material because it is slow, labour-intensive, required intensive care and produced limited numbers of plants. In vitro plant tissue culture transformed this situation by enabling the large-scale production of thousands of genetically uniform, healthy, and disease-free plants within a relatively short period under laboratory conditions. Farmers could now

establish orchards using reliable planting material with consistent growth, higher productivity, and uniform fruit quality, while researchers gained an efficient tool for conserving elite germplasm and rapidly multiplying newly developed cultivars. Furthermore, the integration of tissue culture with molecular biology and genomics has strengthened breeding programmes and continues to play a pivotal role in developing a competitive and self-supporting blueberry industry in India (Abhilash Padhan *et al*., 2025).

As production technologies continued to improve, farmers in Himachal Pradesh, Maharashtra, and Karnataka increasingly recognised blueberries as one of the country's most profitable horticultural crops. Economic returns substantially exceeded those of many conventional fruit crops, with market prices ranging between ₹700–1,200 per 125 g punnet (approximately ₹5,600–9,600 per kg). Commercial growers reported recovering their initial investments within two to three years, while mature plantations under protected cultivation produced 6–12 tonnes per acre. These attractive returns encouraged progressive farmers to diversify into blueberry cultivation, transforming the crop from an experimental venture into a commercially successful enterprise (Agriplast Blog, Blueberry Farming in India: Varieties, Cost & Profit Guide, 2024).

Scientific advancements were further strengthened by supportive government policies that encouraged horticultural diversification across India. At the same time, increasing public awareness of health and nutrition has driven consumer demand for antioxidant-rich fruits. Consequently, blueberries have become increasingly popular through supermarkets and online quick-commerce platforms, despite challenges associated with high production costs and limited technical knowledge of cultivation (Agro & Food Processing, India's Blueberry Farming Enters Growth Phase Despite Cost and Knowledge Challenges, 2026). Although India's blueberry industry is still in its early stages, it has experienced remarkable growth over the past two decades. According to the 2025 report of the International Blueberry Organization (IBO), blueberry cultivation in India covers approximately 725 hectares, with annual production estimated at 5,000–6,000 metric tons. Despite these achievements, domestic production remains insufficient to satisfy national demand, and India continues to import more than 20,000 metric tons of blueberries every year. This substantial demand–supply gap represents one of the greatest opportunities for the future expansion of the industry. The combination of improved cultivars, disease-free planting material, advances in protected cultivation technologies, supportive government initiatives, and rapidly growing consumer demand provides a strong foundation for the sustained long-term growth of blueberry farming in India (Dr. N. D. Negi, Innovations in Blueberry Cultivation, 11th Indian Horticulture Congress, Bengaluru, 2025).

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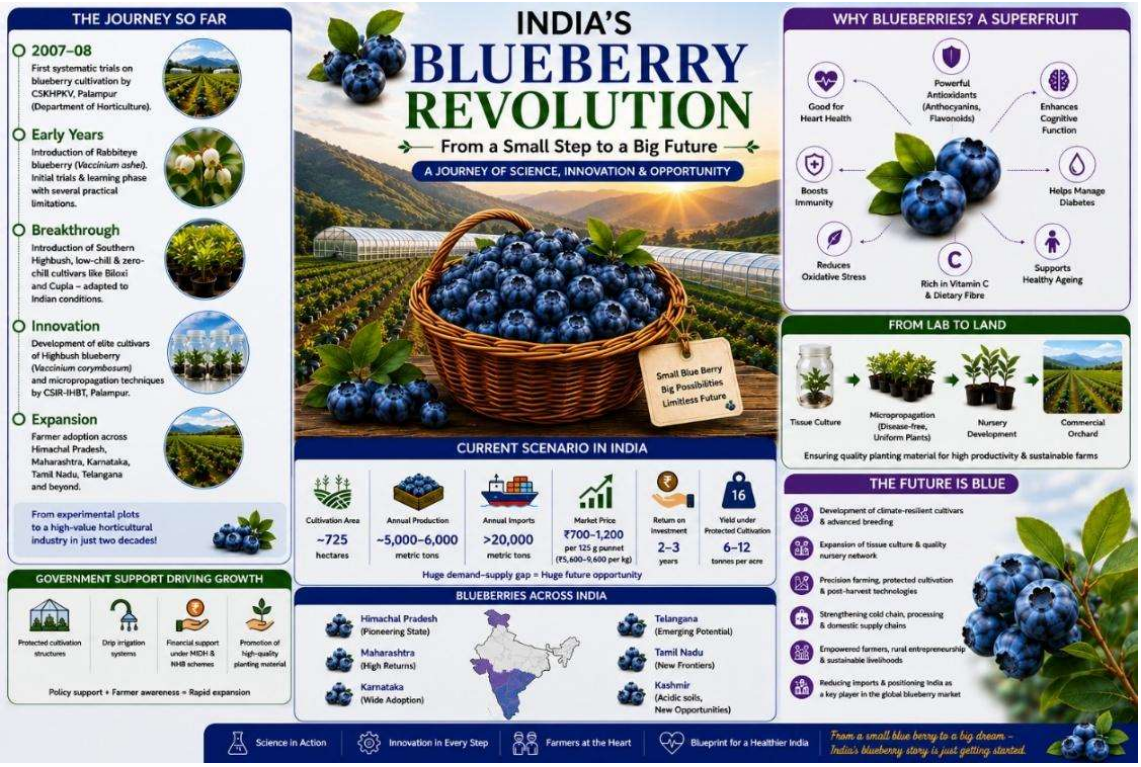


Figure 1. Illustrative infographic of the Indian blueberry revolution. Designed by using ChatGPT (OpenAI). Scientific information compiled from the references cited in this article.

Future of Blueberry Farming in India

The future of blueberry farming in India extends far beyond increasing production. It lies in conserving valuable genetic resources, developing climate resilient cultivars, expanding cultivation into newer regions, creating sustainable livelihood opportunities for farmers and strengthen the country's long term horticultural sustainability. One of the most remarkable scientific milestones was the rediscovery of *Vaccinium piliferum*, a rare wild relative of cultivated blueberries, by researchers from the Society for Education and Environmental Development, CSIR–North East Institute of Science and Technology (CSIR–NEIST) and collaborating institutions in the remote forests of Vijoynagar, Changlang district, Arunachal Pradesh. The species had not been observed for nearly 188 years, and although it was rediscovered in 1923, it was not recorded again until its recent discovery. Today, this wild blueberry relative is being recognised as an invaluable genetic resource for future breeding programmes and biodiversity conservation. Its unique characteristics may contribute to the development of improved cultivars with greater adaptability, disease resistance, and productivity, while also strengthening India's horticultural economy in the years ahead (CSIR–North East Institute of Science and Technology, Researchers Rediscover Rare Wild Blueberry Relative in Arunachal Pradesh After 188 Years, 2026).

The expansion of blueberry cultivation into new geographical regions further demonstrates the crop's enormous future potential. In Kashmir, researchers have shown that blueberries can thrive in naturally acidic soils that are unsuitable for many conventional crops, creating opportunities to utilise previously underused land for establishing high yielding orchards. With market prices approaching ₹2,000 per kilogram and production reaching approximately 6,400 kg per acre, blueberries offer an attractive opportunity for horticultural diversification and income generation in

the region (The Indian Express, Beyond Apples: Why Blueberries Could Be Kashmir's Next Success Story, 2026).

The future of blueberry farming is also being shaped by a new generation of educated entrepreneurs. In Satara district of Maharashtra, young entrepreneur Sanket Shinde, who was initially preparing for the UPSC Civil Services Examination, demonstrated how scientific farming practices and entrepreneurial vision can transform blueberry cultivation into a profitable rural enterprise. His success highlights the growing perception of agriculture not merely as a traditional occupation but as a modern, technology-driven business capable of generating sustainable livelihoods for educated youth (The Indian Express, UPSC Aspirant Sanket Shinde Turns to Exotic Berry Farming in Satara, 2026).

Conclusion

The rise of blueberries in India, from a handful of experimental plantations established just two decades ago to a rapidly growing high-value horticultural industry is a remarkable story of scientific research, technological innovation, entrepreneurship and policy support. Once regarded as an imported luxury fruit, blueberries are now emerging as a symbol of modern Indian horticulture, driven by improved cultivars, biotechnology, protected cultivation, quality planting material, and a growing preference for healthier foods among Indian consumers. Although the revolution is still unfolding, the foundations have already been firmly established for blueberries to become one of India's most successful fruit crops over the coming decades. The future of India's blueberry industry is therefore not merely about cultivating another exotic fruit but it is about strengthening scientific innovation, conserving valuable genetic diversity, empowering farmers, creating rural entrepreneurship, reducing dependence on imports, and positioning India as an important contributor to the global blueberry industry.

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MASTITIS-AFFECTED MILK: A PUBLIC HEALTH CHALLENGE

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Milk is an important source of high-quality nutrition, but its safety is closely associated with the health and management of dairy animals. Mastitis, an inflammation of the mammary gland, is one of the most common and economically important diseases of dairy cattle. Although traditionally considered a disease affecting milk production and animal welfare, mastitis has increasingly become a food-safety and public health concern because of pathogenic microorganisms, antimicrobial residues and the development of antimicrobial resistance (AMR).

Bacterial infection is the predominant cause of mastitis. Important pathogens include *Staphylococcus aureus*, *Streptococcus agalactiae*, *Escherichia coli*, *Streptococcus uberis* and *Klebsiella* spp. Contagious organisms such as *S. aureus* and *S. agalactiae* can spread during milking, whereas environmental pathogens such as *E. coli* and *Klebsiella* spp. are commonly associated with bedding, soil and manure.

Mastitis can occur in clinical as well as subclinical forms. Clinical mastitis may produce visible changes in the udder and milk, whereas subclinical mastitis may remain unnoticed while causing increased somatic cell counts and progressive deterioration of milk quality. Infected cows can produce substantially less milk, and changes in lactose, casein, fat and other milk components can adversely affect the processing quality, shelf life and sensory characteristics of dairy products.

The public health importance becomes particularly evident when mastitis-associated pathogens enter the milk chain. Milk from infected udders may contain pathogenic bacteria and their toxins. *S. aureus* is of particular concern because certain strains can produce enterotoxins that may contaminate milk and dairy products. Therefore, appropriate identification and segregation of affected animals are essential for preventing contaminated milk from reaching consumers.

A second major concern is the extensive use of antimicrobials in mastitis management. Antibiotic therapy is important for appropriately selected cases and contributes to the treatment of infection and protection of animal welfare. However, improper selection, dosing or duration of therapy, together with failure to observe withdrawal periods, can result in antibiotic residues in milk. These residues may cause hypersensitivity reactions, affect the intestinal microbiota and create concerns regarding prolonged antimicrobial exposure. They can also interfere with dairy fermentation by inhibiting beneficial starter cultures.

The problem extends beyond residues to antimicrobial resistance. Repeated and inappropriate antimicrobial exposure creates selection pressure favouring resistant bacteria. Resistant bacteria and antimicrobial-resistance genes may subsequently circulate between animals, humans and the environment through food, manure, wastewater and contaminated ecosystems. Thus, mastitis-associated antimicrobial use contributes to a wider One Health challenge.

Recent evidence illustrates the seriousness of this problem. A nine-year investigation of mastitis pathogens reported multidrug resistance among tested isolates in 45.86% of *E. coli*, 30.4% of *S. aureus* and 22.05% of *S. agalactiae*. The study also observed increasing resistance to some antimicrobials, emphasizing the importance of continuous surveillance and targeted antimicrobial therapy.

Prevention and responsible treatment are therefore the foundation of safe milk production. Good milking hygiene, clean housing, proper teat disinfection, regular udder-health monitoring and early detection of subclinical mastitis can reduce the burden of infection. Where treatment is required, microbiological examination and antimicrobial susceptibility testing can support more targeted therapy. Strict compliance with prescribed withdrawal periods is essential to prevent violative residues from entering the food chain.

Milk-residue surveillance should also be strengthened from the farm to the processing level. Rapid screening methods, immunoassays and other analytical techniques can help detect residues, while confirmatory techniques such as LC-MS/MS provide highly specific identification and quantification. Such surveillance is particularly important where veterinary drug use and regulatory monitoring are inconsistent.

Reducing the need for antibiotics through biosecurity, improved milking practices, vaccination, probiotics and other sustainable approaches can further support antimicrobial stewardship. These approaches are intended to maintain animal health and productivity while reducing unnecessary antimicrobial exposure.

Mastitis therefore represents a problem that extends from the udder to the glass of milk. Protecting public health requires an integrated One Health approach involving healthy animals, hygienic milk production, rational antimicrobial use, strict withdrawal-period compliance, residue monitoring and AMR surveillance. Ensuring the health of the dairy animal is consequently an essential first step toward ensuring the safety of milk consumed by humans.

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ILLEGAL, UNREPORTED AND UNREGULATED (IUU) FISHING: MANAGEMENT, MONITORING AND CONTROL STRATEGIES

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Introduction

Illegal, unreported and unregulated (IUU) fishing is a major challenge to the sustainable management of global fisheries and aquatic ecosystems. It threatens fish stocks, biodiversity, ecosystem functions, food security, livelihoods and the economic sustainability of fisheries-dependent communities. IUU fishing occurs in marine as well as inland fisheries and may involve activities ranging from fishing without authorization and operating in closed areas to under-reporting catches, using prohibited fishing gears, avoiding inspections and exploiting gaps in national and international fisheries governance. The problem extends beyond fishing operations because illegally harvested fish may subsequently enter legitimate supply chains through landing, processing, transportation and marketing activities. IUU fishing is particularly difficult to control in areas where fisheries are geographically extensive, monitoring capacity is limited and institutional responsibilities are fragmented (Temple *et al*., 2022). Recent systematic review evidence has identified socio-economic pressures, weak enforcement and surveillance, limited fisheries data, insufficient stakeholder collaboration and governance gaps as important factors associated with IUU fishing. Effective control therefore requires an integrated approach that combines strong legal and institutional frameworks with monitoring, control and surveillance (MCS), technological innovation, port State measures, traceability, community participation and regional and international cooperation. FAO guidance emphasizes that coastal, flag and port States have complementary responsibilities for preventing, deterring and eliminating IUU fishing through coordinated fisheries governance and enforcement.

Concept and major forms of IUU fishing

IUU fishing encompasses three related but distinct categories of fishing activity: illegal, unreported and unregulated fishing. Illegal fishing refers to fishing activities conducted in violation of applicable national laws, regional fisheries management measures or international obligations, including fishing without a valid licence, fishing in prohibited areas or seasons, exceeding catch limits, using banned gears and targeting protected species. Unreported fishing occurs when fishing activities or catches are not reported, are inaccurately reported or are deliberately concealed from competent fisheries authorities. Such practices reduce the reliability of fisheries statistics and can lead to inaccurate estimates of fishing effort, stock abundance and fishing mortality. Unregulated fishing generally refers to fishing activities conducted in areas or for fish stocks where appropriate conservation and management measures are absent or where fishing activities are inconsistent with applicable international responsibilities. IUU fishing may also involve illegal transshipment, unauthorized landing, false vessel identification, misdeclaration of species or quantities, and movement of catches through supply chains without adequate documentation. Consequently, IUU fishing should not be viewed only as an activity occurring at sea; it can occur at multiple stages of the fisheries value chain. FAO's international framework recognizes a combination of binding and

voluntary instruments addressing flag State, coastal State, port State and market State responsibilities. Understanding these different forms is important because each requires specific monitoring, reporting, enforcement and management mechanisms (Petrossian *et al*., 2015).

Drivers and contributing factors of IUU fishing

The occurrence of IUU fishing is influenced by interacting economic, social, institutional, technological and environmental factors. High demand and market prices for valuable fish and seafood products can create economic incentives to exceed quotas, enter restricted fishing areas or conceal catches. Limited livelihood alternatives, poverty and dependence on fisheries may also contribute to non-compliance, particularly where legal fishing opportunities are limited or regulations are difficult for small-scale fishers to follow. Weak governance is another important driver, particularly where fisheries legislation is unclear, enforcement capacity is insufficient, penalties are inconsistently applied or agencies responsible for fisheries management have overlapping or poorly coordinated responsibilities. Inadequate vessel registration, incomplete catch records, limited fisheries data and insufficient monitoring infrastructure can further create opportunities for illegal activities. Large geographical areas and remote fishing grounds also make conventional surveillance costly and difficult. A recent systematic review in *Aquaculture, Fish and Fisheries* identified socio-economic drivers, weak enforcement and surveillance, limited data availability, insufficient collaboration among stakeholders, fragmented governance and transnational loopholes among the major challenges associated with IUU fishing. Climate variability and declining fish availability may further increase competition for resources in some fisheries, although the influence of environmental factors varies among regions and fisheries. Effective management therefore requires attention not only to enforcement but also to the underlying economic, institutional and social conditions that influence compliance.

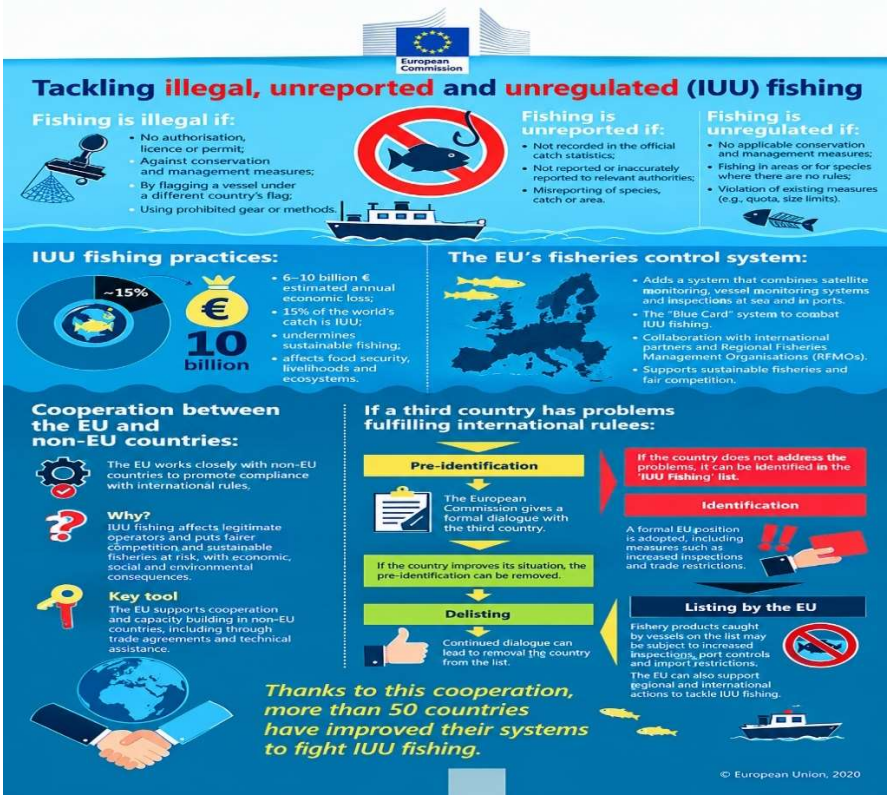


Figure 1. Tackling illegal, unreported and unregulated (IUU) fishing: definitions, impacts, fisheries control measures and international cooperation.

Environmental, economic and social impacts

IUU fishing can produce substantial ecological, economic and social impacts because fishing mortality that is not properly regulated or reported can undermine the sustainability of aquatic resources. Excessive removal of fish may reduce stock abundance, alter population structure and affect the recruitment and recovery capacity of exploited species. Illegal fishing gears and practices may also increase the capture of juveniles, spawning individuals and non-target species and may damage sensitive aquatic habitats (Simataa *et al*., 2025). Unreported catches create additional difficulties for fisheries managers because stock assessments and management decisions depend on accurate information about catch, effort and fishing mortality. When actual fishing pressure is underestimated, management measures such as catch limits, closed seasons and recovery programmes may not adequately protect fish stocks. The economic consequences include reduced income for legally operating fishers, unfair competition, loss of licensing and tax revenues, reduced profitability of responsible fishing enterprises and potential losses throughout the seafood value chain. Social impacts may include reduced employment opportunities, declining household income and reduced availability of fish as an important source of animal protein. IUU products entering legitimate markets can also weaken seafood traceability and create difficulties for processors, exporters and consumers seeking assurance about the legal origin of fishery products. The consequences are therefore interconnected, linking ecological degradation with economic and social vulnerabilities. Addressing IUU fishing is consequently important not only for fisheries conservation but also for food security, sustainable livelihoods and responsible seafood production.

Management, monitoring and control strategies

Effective control of IUU fishing requires an integrated management system in which legislation, monitoring, enforcement, technology, traceability and stakeholder participation operate together. FAO's recent technical guidance emphasizes that national systems should consider responsibilities across fishing operations, monitoring, control and surveillance, transshipment and port State measures. The following complementary strategies are particularly important for improving the prevention, detection and control of IUU fishing.

Legal and institutional frameworks

Strong legal and institutional frameworks provide the foundation for preventing and controlling IUU fishing. Fisheries legislation should clearly establish licensing requirements, fishing zones, authorized gears, catch limits, closed seasons, reporting obligations, landing requirements and penalties for violations. Regulations should be scientifically supported, transparent and practical to implement. Clear responsibilities should also be assigned to fisheries departments, maritime authorities, coast guards, customs, port authorities and other agencies involved in fisheries monitoring and enforcement. At the international level, several instruments provide a framework for combating IUU fishing, including the FAO International Plan of Action to Prevent, Deter and Eliminate IUU Fishing and the Agreement on Port State Measures (PSMA). FAO describes the PSMA as the first binding international agreement specifically targeting IUU fishing, with the objective of preventing vessels engaged in IUU fishing from using ports and landing their catches (Lim *et al*., 2025). Effective legislation, however, depends on implementation capacity, regular inspection, consistent enforcement and cooperation among responsible institutions. Recent evidence from India indicates that although policy and technological measures have been developed, gaps remain between policy and implementation, including fragmented MCS oversight, inconsistent vessel tracking and limited inter-state coordination. Strengthening institutional coordination and

developing clear operational procedures are therefore essential components of effective IUU management.

Fisheries monitoring and surveillance

Monitoring, control and surveillance (MCS) are central to the practical implementation of fisheries regulations. Monitoring involves the collection and analysis of information on fishing activities, catches, fishing effort, species composition, fishing locations and vessel operations. Control involves establishing and implementing rules and administrative procedures that ensure fishing activities comply with management measures, while surveillance involves observing and verifying fishing activities through inspections, patrols, vessel tracking and other enforcement mechanisms. FAO's MCS guidance identifies national MCS systems, operations, procedures and tools as important components for assessing and strengthening fisheries enforcement. MCS systems may include vessel inspections, onboard observers, patrol vessels, aerial surveillance, landing-site inspections, electronic reporting and risk-based monitoring. Effective MCS should be proportional to the characteristics of each fishery because the requirements of large industrial fleets may differ substantially from those of small-scale fisheries. Integration of information among fisheries authorities, coast guards, port authorities and other enforcement agencies can reduce duplication and improve response times. Regular evaluation of MCS performance is also necessary to identify weaknesses and ensure that limited financial and human resources are directed toward areas with higher compliance risks.

Vessel monitoring and tracking technologies

Vessel monitoring and tracking technologies have become increasingly important for detecting potentially illegal fishing activities over large geographical areas. Vessel Monitoring Systems (VMS) can provide information on vessel positions, movements and fishing activity to fisheries authorities, while Automatic Identification Systems (AIS) provide vessel identification and location information under applicable regulatory requirements. Satellite-based tracking and remote sensing can complement these systems by providing information on vessel activity in areas where conventional patrols are difficult or expensive. Such technologies can help identify vessels operating inside restricted zones, fishing during closed periods or showing movement patterns that warrant further inspection. FAO identifies VMS among the tools that can strengthen fisheries MCS and improve the ability of authorities to track fishing vessels. However, technological systems are most effective when linked with reliable vessel registration, licensing databases, trained personnel and established procedures for investigating alerts. In India, recent review evidence indicates that vessel tracking and satellite-based communication technologies have been adopted, but implementation of some measures, including AIS and logbook requirements, remains incomplete or inconsistent. Future vessel monitoring systems should therefore focus not only on increasing technological coverage but also on improving data integration, maintenance, enforcement capacity and inter-agency information sharing.

Port State measures and catch documentation

Port State measures provide an important mechanism for controlling IUU fishing by preventing vessels engaged in illegal activities from using ports and landing illegally harvested catches. The FAO Agreement on Port State Measures establishes legally binding international measures for preventing, deterring and eliminating IUU fishing through controls on foreign fishing vessels seeking access to designated ports. Port inspections can include verification of vessel identity, fishing

licences, catch documentation, fishing gear, logbooks and information concerning previous fishing operations. Catch documentation and traceability systems can further strengthen control by linking fishery products with the vessels, fishing areas and landing events from which they originated. This reduces opportunities for illegally harvested fish to be mixed with legally caught products and subsequently enter domestic or international markets. Effective port controls are particularly important because enforcement opportunities at sea may be limited by the size and remoteness of fishing areas. FAO's 2026 technical guidance incorporates port State measures, transshipment and catch documentation within the broader responsibilities of States for combating IUU fishing. Strengthening port inspection capacity, digital documentation, information exchange and risk-based inspection procedures can therefore improve the detection and prevention of illegal catches throughout the seafood supply chain.

Electronic monitoring and digital technologies

Rapid development of digital technologies has created new opportunities for improving fisheries monitoring and enforcement. Electronic monitoring systems can use onboard cameras, sensors and recording devices to document fishing operations, catch composition, discards, gear use and vessel activities. Electronic logbooks and electronic reporting systems can improve the speed and accuracy of fisheries data transmission compared with conventional paper-based reporting. Satellite imagery, machine learning and artificial intelligence can also assist in identifying unusual vessel behaviour and prioritizing vessels or locations for inspection. Combining information from AIS, VMS, electronic monitoring, catch records and remote sensing can create a more comprehensive picture of fishing activity. However, digital technologies should complement rather than replace field inspections, fisheries officers and other enforcement mechanisms. Their effectiveness depends on data quality, system interoperability, trained personnel, reliable communication networks and clear legal procedures governing the use of electronic information. In the Indian context, recent research has highlighted the adoption of technologies such as biometric identification, online registration and satellite-based communication while also identifying implementation gaps in vessel tracking and data coordination. Future digital MCS systems should therefore prioritize interoperability, real-time data analysis, cybersecurity, appropriate data governance and the development of institutional capacity to convert technological information into practical enforcement actions.

Community participation and co-management

Fishing communities can make an important contribution to IUU fishing prevention because fishers possess extensive knowledge of local fishing grounds, seasonal fishing patterns, species distribution and fishing practices. Community participation can include fisher organizations, local monitoring groups, participatory rule-making, community reporting mechanisms and co-management arrangements between government agencies and resource users. Meaningful participation can improve understanding of regulations and increase acceptance of management measures when local knowledge and livelihood conditions are considered during decision-making. Community-based approaches are particularly relevant in small-scale fisheries where government surveillance resources may be limited across numerous landing centres and fishing grounds. Awareness programmes can also improve knowledge of licensing requirements, closed seasons, protected species, legal fishing gears and the ecological consequences of overfishing. However, community participation should complement formal legal enforcement rather than replace it. Recent research on India has identified limited stakeholder engagement and community participation as constraints on cohesive MCS implementation and has emphasized greater involvement of fisher communities

in decision-making. Strengthening trust between fisheries authorities and communities, providing accessible reporting mechanisms and involving fishers in management planning can therefore contribute to improved compliance and sustainable resource use.

Regional and international cooperation

IUU fishing frequently crosses national boundaries, making regional and international cooperation essential for effective management. Fishing vessels may operate across multiple jurisdictions, while illegally harvested fish may pass through several countries before reaching consumers. Cooperation among flag States, coastal States, port States, market States and regional fisheries management organizations can improve information exchange and enforcement coordination. Shared vessel databases, harmonized reporting requirements, joint surveillance, coordinated port inspections and information exchange concerning suspected IUU vessels can reduce opportunities for offenders to exploit differences among national systems. FAO's international framework assigns complementary responsibilities to flag, coastal and port States and recognizes cooperation as an important component of fisheries governance. Regional cooperation is particularly important for transboundary and highly migratory fish stocks. In the Indian Ocean region, strengthening coordination among neighbouring countries can improve the management of shared resources and reduce enforcement gaps. Recent research on the Bay of Bengal has highlighted IUU fishing as a significant fisheries-management concern and emphasized the importance of regional cooperation for improving sustainability. International cooperation should therefore include not only enforcement activities but also scientific data sharing, capacity building, technology transfer and harmonization of fisheries management standards (Leonardo *et al*., 2022).

Challenges in controlling IUU fishing

Despite improvements in fisheries legislation, surveillance and monitoring technologies, controlling IUU fishing remains difficult because of the large geographical scale of fisheries, limited enforcement resources, fragmented governance and differences in national capacities. Developing countries may face shortages of patrol vessels, trained personnel, monitoring equipment and financial resources, making continuous surveillance difficult. Fisheries information may also be incomplete or distributed across multiple agencies that do not routinely share data. Technological systems can be expensive to install and maintain, and their effectiveness may be reduced when vessels are not adequately registered or when reporting requirements are inconsistently implemented. Weak institutional coordination can further create gaps between policy development and practical enforcement. A recent review of India's MCS system reported inconsistent vessel tracking, limited stakeholder engagement, poor inter-state collaboration and gaps between policy and implementation. Similar challenges have been identified in the 2025 systematic review of IUU fishing in Africa, which highlighted weak enforcement, limited data availability, governance gaps, socio-economic pressures, transnational loopholes and insufficient collaboration. Another challenge is ensuring that enforcement measures do not disproportionately affect small-scale fishers who may have limited capacity to comply with complex reporting or technological requirements. Effective policy should therefore combine enforcement with capacity building, accessible compliance mechanisms and livelihood-sensitive management. Long-term institutional strengthening is required rather than relying only on short-term enforcement operations.

Emerging approaches and future perspectives

The future management of IUU fishing is likely to increasingly depend on integrated digital monitoring, data-driven enforcement, supply-chain traceability and stronger collaboration among

governments, fishing communities, researchers and industry stakeholders. Satellite imagery, AIS, VMS, electronic monitoring and artificial intelligence can generate large datasets that can be analysed to identify unusual vessel behaviour and prioritize inspections. Risk-based MCS can allow authorities to concentrate limited resources on vessels, fishing areas and activities associated with higher compliance risks. Digital catch documentation and traceability can improve transparency from capture to market and make it more difficult for illegally harvested fish to enter legitimate supply chains. FAO's 2026 technical guidance brings together responsibilities relating to fishing operations, monitoring, control and surveillance, transshipment and catch documentation, demonstrating the growing importance of integrated approaches to IUU management. Future strategies should also strengthen scientific stock assessment, fisheries data collection, electronic reporting, vessel registration and institutional coordination (Auld *et al*., 2023). For India and other developing fisheries nations, priorities include improving vessel tracking, strengthening inter-agency coordination, increasing community participation and addressing socio-economic barriers to compliance. Technological innovation should therefore be accompanied by appropriate legislation, trained personnel, reliable infrastructure and transparent data governance. A balanced approach combining technology, science, enforcement and community participation will be important for building fisheries management systems that are both effective and socially appropriate.

Conclusion

IUU fishing is a complex and multidimensional challenge that threatens the ecological sustainability, economic viability and social benefits of fisheries. Its impacts extend from fish stocks and aquatic ecosystems to fishing communities, seafood markets and national economies. Effective control requires an integrated framework combining clear legislation, institutional coordination, monitoring, control and surveillance, vessel tracking, electronic monitoring, port State measures, catch documentation, traceability, community participation and regional and international cooperation. Recent evidence shows that weak enforcement, inadequate fisheries data, fragmented governance and limited stakeholder participation remain important barriers to effective IUU management. The increasing availability of satellite monitoring, digital reporting, artificial intelligence and electronic traceability provides new opportunities to strengthen fisheries governance, but these technologies must be supported by appropriate institutions, trained personnel and enforceable regulations. For sustainable fisheries and aquaculture-related food systems, reducing IUU fishing is essential for protecting aquatic biodiversity, improving resource management, supporting legitimate fishing livelihoods and ensuring the long-term availability of fishery resources. A coordinated, science-based and participatory approach will be essential for preventing, detecting and controlling IUU fishing at local, national, regional and global levels.

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READING NATURE, SHAPING AGRICULTURE'S FUTURE: FROM FARMER WISDOM TO SMART AND RESILIENT FARMING

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Abstract

Nature continuously provides signals about emerging risks, constraints and opportunities in agriculture. Changes in temperature, rainfall patterns, soil moisture, crop growth, pest and disease incidence, water availability, biodiversity and soil biological activity are increasingly influencing agricultural productivity and farm livelihoods. Rising temperatures, erratic rainfall, recurrent floods and droughts, declining soil organic matter, nutrient imbalance, soil degradation and biodiversity loss are making conventional production systems more vulnerable to climatic and ecological stresses. These changes underline the need to move from reactive farming, where problems are addressed after they become visible, towards responsive and anticipatory agriculture based on early observation, scientific assessment and timely action. Farmers can strengthen resilience by maintaining healthy soils, improving water-use efficiency, adopting balanced and site-specific nutrient management, diversifying crops, conserving biodiversity and selecting climate-resilient varieties. Modern tools such as weather forecasting, soil testing, remote sensing, sensors, digital advisories and artificial intelligence can complement farmers' traditional knowledge and field observations. The future of agriculture will therefore depend on integrating ecological understanding with scientific knowledge, farmer experience and appropriate technology. Working with nature rather than against it can help create agricultural systems that are productive, resource-efficient, economically viable, climate-resilient and environmentally sustainable, while safeguarding soil, water, biodiversity and food security for present and future generations.

Keywords: Nature-based agriculture; climate resilience; soil health; biodiversity; climate-smart agriculture; sustainable agriculture; regenerative agriculture; water-use efficiency; balanced nutrient management; resilient crops; digital agriculture; farmer knowledge; ecological signals; resource-use efficiency; food security.

Introduction

Agriculture has always depended on the ability of farmers to read and respond to nature. Long before modern sensors, satellites, soil laboratories and digital platforms, farmers observed changes in soil, weather, plants, insects, water, and landscape to guide decisions on sowing, irrigation, nutrient application and crop protection. These observations represent a form of ecological intelligence developed through generations of experience. Today, however, agricultural systems are facing increasingly complex and interacting pressures - climate variability, soil degradation, declining soil organic matter, nutrient imbalance, water scarcity, biodiversity loss, emerging pests and diseases, and growing demand for food produced with fewer environmental costs. Under these conditions, learning to read nature's signals is becoming not only a traditional skill but also a foundation for scientifically informed and climate-resilient agriculture.

Nature continuously provides signals about the condition of agricultural ecosystems. Changes in leaf colour, plant vigour, root development, flowering behaviour, weed communities, insect populations, soil structure, earthworm activity, moisture status and water movement can indicate emerging problems or opportunities. Similarly, changes in rainfall patterns, temperature, wind, humidity and soil moisture influence crop growth and nutrient availability. Some signals are visible to the farmer, while others require measurement through soil testing, weather stations, remote sensing, sensors or laboratory analysis. The challenge is therefore not simply to observe nature, but to correctly interpret these signals and convert them into timely management decisions.

Modern agricultural science provides powerful tools for strengthening this process. Soil health assessments can reveal changes in pH, electrical conductivity, organic carbon, nutrient availability and physical condition. Weather forecasting and agro-advisories can help farmers adjust sowing, irrigation and crop-protection decisions. Remote sensing, geographic information systems, drones and proximal sensors can detect spatial and temporal variation within fields. Digital agriculture, artificial intelligence and machine learning are increasingly capable of integrating these diverse sources of information to provide location- and crop-specific recommendations. Thus, the future of agriculture need not represent a choice between traditional knowledge and modern technology; rather, it can integrate farmer experience with scientific measurement and digital intelligence.

The central principle is to move from reactive agriculture to responsive agriculture—from correcting problems after crop symptoms appear to detecting early signals and acting before damage becomes severe. This requires greater attention to the soil–plant–water–atmosphere continuum and to the biological processes that sustain productivity. A healthy soil, diverse cropping system, efficient water use, balanced nutrition, functional soil biology and appropriate crop diversification can improve the capacity of farms to absorb climatic and ecological shocks.

“Reading Nature’s Signals, Shaping the Future of Agriculture” therefore represents a broader vision of agricultural transformation. It emphasizes observation, measurement, interpretation and timely action as interconnected components of intelligent farming. The future farmer will increasingly combine the wisdom of the field with the evidence of science and the predictive capacity of digital technologies. Such an approach can help transform agriculture from an input-intensive production system into a knowledge-intensive, resource-efficient, regenerative and climate-resilient system, capable of producing nutritious food while protecting the natural resources on which future agriculture depends.

1. Nature's first message - Link farming to natural balance

Farming isn't a system outside of nature. A farmer sows seeds , but their germination , plant growth, and crop production depend on soil , water , air , temperature , microorganisms, and a host of other natural processes. If the natural balance is disturbed, agriculture will also be affected. Deforestation affects the water cycle. Imbalanced nutrient use can reduce soil quality. Therefore, farmers should consider soil not only a means of production , but also a source of energy. Living and vital natural resources Should be accepted. To achieve this, soil testing, balanced fertilizer use, cow dung manure, compost, vermicompost, green manure, crop rotation, and proper use of crop residues are essential. This will increase soil organic matter and the number of beneficial microorganisms.

2. Soil Message - We need healthy soil, not just fertile soil

The Green Revolution played a significant role in increasing food grain production in India. The use of improved varieties, irrigation, and fertilizers led to large increases in production. However,

growing the same types of crops for long periods of time and not adding enough organic matter to the soil has affected soil quality in many areas. Soil doesn't just need nitrogen, phosphorus, and potash. Continuous cropping can also lead to deficiencies in sulfur, and zinc, boron, iron, other micronutrients. Therefore, Balanced nutrition based on soil testing, cowdung manure, compost, vermicompost, green manure, organic fertilizers, and chemical fertilizers should be used by the farmer in a balanced manner as needed. Incorporating crop residues into the field increases soil organic matter and improves soil health.

3. The message of water - Understand the value of every drop

Water is the most important resource for agriculture. In many areas, dependence on groundwater for irrigation is steadily increasing. If groundwater continues to be used at a rate faster than its natural recharge, severe water shortages could occur in the future. Therefore, not only the use of water, but also storage and recharge is also necessary. Farmers can create a water budget for their fields. Crop selection should be based on rainfall, soil water-holding capacity, and the crop's water requirements. To achieve this, methods such as rainwater harvesting, farm ponds, bunding, contour bunding, groundwater recharge, drip irrigation, sprinkler irrigation, mulching, and reduced tillage can be adopted. Even for water-intensive crops, water-saving irrigation methods are essential.

4. Rain's message - Plan your farming according to the changing weather

In the past, farmers used to plan their farming based on long-standing experience and traditional weather indicators. But now, weather patterns are changing rapidly. Therefore, relying solely on past experiences is no longer sufficient. Now the farmer plans farming based on weather forecasts. Depending on the weather, necessary changes can be made in the timing of irrigation, harvesting sowing and pest and disease control. Weather-related agricultural advisories should reach villages and farmers in simple language. Regular engagement with farmers is essential, as are *Krishi Vigyan Kendras (KVKs)*, agricultural experts, and local agricultural advisory services.

5. The message of climate change - Don't rely on monocultures.

Rising temperatures, irregular rainfall, drought, floods, hailstorms and sudden weather events can affect crop production. Therefore, farmers should not depend on only one crop. crop diversification It is safer to adopt this. Along with cereals , pulses , oilseeds, vegetables, fruits, fodder crops, animal husbandry, and agro-forestry can be incorporated into farming. If one crop fails for some reason, a farmer can earn income from other crops, animal husbandry, or horticulture. Thus, farming should not be considered solely about crop production. Integrated Farming System should be developed as.

6. The Message of the Seed - The Right Seed is the First Step to Success

The importance of seeds increases during climate change. Farmers should not only choose high-yielding varieties, but also those suited to the climate and soil of their region. Varieties that are drought-toleran, heat-tolerant, quick-maturing, waterlogging-tolerant, and pest and disease-tolerant can be useful for farmers. Seed treatment reduces the risk of seed- and soil-borne diseases and promotes good early plant growth. Therefore, farmers should remember: appropriate variety + certified seed + seed treatment + timely sowing = a strong foundation for a good harvest.

7. Message of crop residues - Do not burn them, make them farm wealth

The residue left after harvesting a crop is not a burden for the farmer , but rather a useful organic resource. Burning crop residue causes air pollution and destroys valuable organic matter in the field.

By incorporating crop residue into the field, organic matter can be increased in the soil. It can also be used as mulch. It can also be used in shredders, residue management equipment, compost, organic fertilizer, biogas, and animal feed. Crop residues are not waste , they are the organic capital of the farm.

8. The message of biodiversity - Diversity is security

Growing the same crop repeatedly can increase the risk of pests and diseases in the field and can increase the impact of weather. In contrast, crop rotation, mixed farming, intercropping and agro-forestry increase diversity in the field. Pulse crops help in improving soil fertility. Oilseeds can become a source of additional income. Fruit-bearing and useful trees not only provide additional income to the farmer but also protect the environment. Nature's message is clear - increase diversity, reduce risk.

9. The message of pests and diseases - Not every pest is an enemy

Not all farm insects are harmful. Many beneficial insects help control harmful pests. Therefore, it is not advisable to use chemical pesticides repeatedly without need. Farmers should *Integrated Pest Management* This may include healthy seeds, regular field monitoring, pheromone traps, neem-based treatments, and, if necessary, chemical control as per scientific advice.

10. The message of modern technology - Bring knowledge to the farm

New technology is useful only if it solves a farmer's real problem. Weather forecasting, soil testing, mobile-based agricultural advisories, drones, sensors, satellite images, and remote sensing can make farming more scientific. Sensor-based irrigation systems can save water. Drones can save time and labor in spraying. Satellite-based monitoring can help understand crop health. Before adopting any new technology, farmers should ask three questions: 1. Will it reduce the costs ? 2. Will it increase production or quality ? 3. Will it protect soil, water, and the environment? If the answer to all three is positive, then the technology can be useful for the farmer.

11. The message of nutrients - Balanced nutrition is the foundation of a healthy crop

Simply providing more nitrogen to a crop does not result in higher yields. Plants need nitrogen , phosphorus, and potash, as well as sulfur , zinc , iron, and other essential nutrients. Therefore, the use of fertilizers Based on soil testing and crop requirements This should be done. Balanced use of organic manure, biofertilizers, crop residues, and appropriate specialized fertilizers can increase nutrient efficiency. Before adopting any new fertilizer or agricultural practice, its reliability should be verified and advice should be sought from agricultural universities and agricultural experts.

12. The message of low-cost farming - More profit with less expenditure

The real success of a farmer lies not only in higher production , but also in *higher net income* Good seeds , timely sowing , soil testing, balanced nutrition, use of local biological resources, water conservation, labor-saving agricultural equipment, collective procurement, collective marketing, and crop diversification are important for low-cost farming. In simple terms: *Net income = total income - total expenditure.* Therefore, farmers should evaluate each technology based on production costs, water consumption, labor requirements, and the final net income.

13. Farmer income and market message - A fair price is essential along with production.

Producing a good harvest is not enough. Farmers cannot achieve a strong economic status if they do not receive a fair price for their produce. Therefore, storage, processing, value addition, and direct access to markets are also important components of farming. Farmer producer organizations,

cooperatives, farmer groups, and collective marketing can enhance farmers' bargaining power. Locally processing pulses, oilseeds, fruits, vegetables, and dairy products can generate additional income and employment opportunities.

14. The message of animal husbandry - Put farming and animal husbandry together

Crop and animal husbandry have always been intertwined in Indian agriculture. Animal dung is useful in producing organic fertilizer and compost. Farm fodder can be used for livestock. Thus, farming and animal husbandry can complement each other. Farming costs can be reduced by producing compost, vermicompost, biogas, and organic fertilizer from dung.

15. Message from farmers and nature - Protecting both together

The farmer of the future will not only be a person who produces food , but Protector of *soil, water, biodiversity and natural resources.* A farmer who increases soil organic matter, conserves water, practices crop diversity, manages crop residues properly, and uses agricultural chemicals judiciously protects not only his or her farm but also the environment of society as a whole. Therefore, policies are needed that encourage farmers who protect natural resources. “Farmers should protect nature and nature should protect the farmer's income and livelihood.”

Figure 1 shows the techniques for understanding nature's warnings and finding appropriate solutions for agriculture , farmers and a safe future, which are the need of the hour.



Figure 1:Understanding nature's warnings and finding appropriate solutions for agriculture, farmers and a safe future

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Messages from Nature with 15 solutions for farmers to understand nature, conserve resources, increase farm production, and stabilize income are being summarised in Table 1 and displayed in Figure 2.

Table 1. Fifteen Solutions messages for farmers from Nature

S. No.	Nature's Message	Meaning of the Message	Solution for Farmers
1	**Soil says - Keep me healthy**	Soil fertility is declining, and organic matter and humus are decreasing.	• Conduct soil testing and adopt balanced nutrient management. • Use organic manure, compost and vermicompost. • Adopt crop rotation and weed management.
2	**Water says - Value every drop**	Groundwater levels are declining and water scarcity is increasing.	• Harvest rainwater and build farm ponds. • Adopt drip and sprinkler irrigation. • Irrigate according to crop requirements.
3	**Rain says - My pattern is changing**	Rainfall is becoming irregular; more rain is occurring in shorter periods, while drought and flood events are increasing.	• Pay attention to weather forecasts. • Adjust sowing and irrigation schedules. • Strengthen water conservation and drainage management.
4	**Temperature says - I am rising**	Heatwaves, unusual cold and high temperatures are increasingly damaging crops.	• Choose heat-tolerant varieties. • Use mulching, light irrigation and shade management. • Adjust sowing and harvesting times.
5	**Seed says - Choose me wisely**	The wrong variety, poor-quality seed and inappropriate sowing time can reduce production.	• Choose certified and climate-resilient varieties. • Treat seeds and sow at the right time. • Select varieties adapted to local conditions.
6	**Crop residue says - Do not burn me**	Burning crop residues damages soil, air and the environment.	• Incorporate residues into the soil or make compost. • Use mulchers, zero tillage and composting.

S. No.	Nature's Message	Meaning of the Message	Solution for Farmers
			• Use residues as fodder or animal feed.
7	**Biodiversity says - Diversity is security**	Dependence on a single crop increases the risk from pests, diseases and price fluctuations.	• Adopt crop rotation, mixed farming and intercropping. • Include pulses, oilseeds and horticultural crops. • Promote agroforestry and perennial plants.
8	**Insect says- Not every insect is an enemy**	Excessive use of chemicals can harm beneficial insects and increase pest resistance.	• Adopt Integrated Pest Management (IPM). • Monitor pests and use economic threshold levels. • Use neem-based pesticides and scientific advice.
9	**Nutrients say - Give balanced food**	Nitrogen alone cannot keep a crop healthy; nutrient deficiency or excess creates an imbalance.	• Adopt soil-test-based 4R nutrient management. • Use organic sources and biofertilizers. • Apply the right dose at the right time and place.
10	**Technology says- Adopt me, gain benefits**	Modern technology can save time, labour, costs and natural resources.	• Use drones, sensors, mobile advisories and digital tools. • Use appropriate farm machinery and digital technologies. • Follow crop- and weather-based advisories.
11	**Farmer's income says - Reduce costs, increase value**	Higher production must be accompanied by cost control and better prices to increase farm income.	• Promote collective purchase and collective marketing. • Adopt processing, storage and value addition. • Join FPOs and cooperative organizations.
12	**Livestock says - Connect us with farming**	Separating crop and livestock systems increases risks and production costs.	• Use cow dung and urine to prepare biofertilizers and biopesticides. • Integrate fodder and crop residues into the farming system.

S. No.	Nature's Message	Meaning of the Message	Solution for Farmers
			• Include dairy, goat and poultry enterprises.
13	**Trees say - Plant us, save the future**	Trees help maintain environmental balance, conserve soil and provide additional income.	• Adopt agroforestry and plant fruit and forest trees. • Plant trees along farm boundaries and on pastureland. • Explore carbon credits and environmental benefits.
14	**Community says - Collective effort brings success**	Collective action by small farmers can improve productivity, security and bargaining power.	• Form farmer groups, FPOs and cooperatives. • Undertake collective purchase of seed, fertilizer and machinery and collective marketing. • Share knowledge and make decisions collectively.
15	**Risk says - Be prepared, stay secure**	Natural disasters can cause losses at any time.	• Take crop insurance. • Prepare a disaster-management plan. • Adopt climate-resilient farming practices.

Figure 2 displays Fifteen Solutions messages for farmers from Nature.



Figure 2: Fifteen Solutions messages for farmers from Nature

16. Golden Rules for Farmers for Sustainable Agriculture

Farmers can build productive, resilient and profitable farms by following a few essential rules. They should choose the *right seed* suited to local soil, climate and markets, and follow the *right time* for sowing, irrigation and harvesting. *Balanced nutrition*, guided by soil testing, improves crop health and fertilizer-use efficiency. Every drop of water should be conserved through rainwater harvesting, moisture conservation and efficient irrigation. *Crop diversification* reduces risks, improves soil health and creates additional income opportunities. Farmers should keep *production costs low* while improving productivity, value addition and market access to increase *farm income.* Sustainable agriculture rests on five pillars: *soil health, water management, biodiversity, climate resilience and economic stability.* Farmers should test their soil, sow on time, conserve water, diversify farming systems and *work with nature*.

17. Action plan

Action plan for climate-resilient agriculture at the village level: Each village can develop a climate-resilient agricultural plan tailored to its local conditions and risks. Such a plan will be effective only if it takes into account the actual situation of the village's soil, water, rainfall, crops, livestock, and local markets (**Table 2**).

Table 2. Action plan for climate-resilient agriculture at the village level

Area	**Major tasks for the farmer**
Water	Rainwater harvesting water budgeting and groundwater recharge
Soil	Soil testing, organic matter and balanced nutrition
Seed	Climate-tolerant varieties suited to local conditions
Crops	Mixed farming, crop diversification and crop rotation
Insect-disease	Integrated Pest and Disease Management
Agricultural machinery	Availability of collective farm machinery and equipment rental
Season	Local weather forecast and agricultural advice
Animal husbandry	Coordination of crop and animal husbandry
Market	Farmer Producer Organizations and Collective Marketing
Risk	Crop Insurance and Disaster Management

(ii) New role of agricultural research and extension services

- In a changing climate, agricultural research must focus more on the real problems faced by farmers. Technologies and varieties must be developed that can produce with less water, tolerate higher temperatures, resist pests and diseases, and reduce farmers' costs.
- Agricultural extension services should not be limited to production techniques alone. Farmers should also be provided with assistance in weather-based advisories, risk management, water conservation, natural resource protection, and market linkages.

This system can become more effective through joint efforts of agricultural science centres, agricultural universities, farmer producer organisations, cooperative institutions and private sector.

(iii) Nature's message to the government and policy makers

Nature's signals are important not only for farmers but also for governments and policymakers. Future agricultural policies should prioritize the following:

- Promote water conservation and groundwater recharge.
- Promoting climate-tolerant seeds and technologies.

- Paying attention to soil health and balanced nutrition.
- Promoting water budgeting and micro irrigation.
- Agro-forestry and conservation of biodiversity.
- To arrange market and fair price for crop diversification.
- To promote collective farm mechanization for small and marginal farmers.
- Strengthening farmer producer organizations and cooperative marketing.
- Strengthening agromet advisories at the local level.
- To provide economic and social incentives to farmers for conservation of natural resources.

The ultimate objective of these policies should be to create an agricultural system that Safe , profitable , sustainable and resource-conserving yes.

(iv) Changes are also needed in farmer training.

Today, farmer training shouldn't be limited to crop production. Farmers should also be educated on topics such as soil health, water budgeting, climate risk, weather-based agricultural advice, climate-resilient farming, balanced nutrition, use of biological resources, integrated management of pests and diseases, digital agriculture, cost-benefit assessment, marketing, and value addition. Training will be more effective if local examples, on-farm demonstrations, experiences of successful farmers, simple diagrams, mobile-based agricultural advice and practical exercises Join in.

Summary and Conclusion

Nature is constantly signaling to us: *“Keep me safe , and I will keep you safe”.* Climate change, uneven rainfall, rising temperatures, depleting groundwater, declining soil quality and the increasing incidence of pests and diseases are not just isolated incidents. They signal that the time has come for necessary reforms to the current farming system. Farmers do not have to struggle against nature , but rather We have to understand nature and do farming in collaboration with it. Successful farming in the future will be one that uses less water, controls costs, maintains healthy soil, balances nutrient use, increases crop diversity, promotes animal husbandry and horticulture, and makes judicious use of modern technology and market intelligence. We need to create an agricultural system that Keep the soil healthy, water safe, seeds strong, crops diverse, farmer's income stable and environment safe Nature's message is simple: " *Keep me safe, and I'll keep you safe.*" Farmers understand this message best, as their livelihoods depend directly on nature. Therefore, farmers are not only affected by climate change , but also a key to its solutions. Key Partners India's secure agricultural future begins on the farm—where soil and water are protected , biodiversity is enhanced , farmer incomes are secured, and natural resources are preserved for future generations. This is the strong foundation of sustainable agriculture and a prosperous rural India. To ensure agriculture sustainability: *Respect Nature - Conserve Resources - Practice Sustainable Farming - Build a Prosperous Life.*

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ADVANCED WATER QUALITY MANAGEMENT FOR SUCCESSFUL ORNAMENTAL FISH CULTURE

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Introduction

Ornamental fish culture involves the breeding and rearing of attractive freshwater and marine fishes for aquarium and commercial purposes. Water quality is one of the most important factors affecting ornamental fish health and production. Parameters such as temperature, pH, dissolved oxygen, ammonia, nitrite, nitrate, turbidity and microbial load must be properly controlled. Continuous changes in these parameters can cause stress and increase the risk of diseases. However, modern technologies provide continuous monitoring and improved control of culture water.

Importance of Water Quality Management

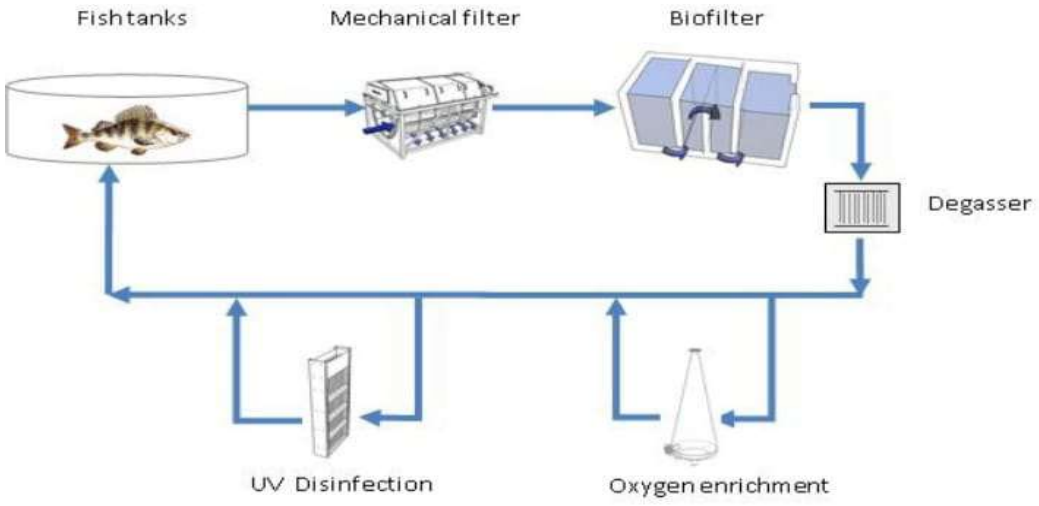
Good water quality helps to:

- Maintain healthy growth of ornamental fishes.
- Improve survival and breeding performance.
- Maintain natural body colour and appearance.

Ammonia and nitrite are particularly important because their accumulation can negatively affect fish health. Therefore, regular monitoring and biological filtration are essential in intensive culture systems.

Advanced Technologies for Water Quality Management

Recirculating Aquaculture System (RAS)



Caption: Figure 1. Recirculating Aquaculture System (RAS) used in ornamental fish culture.

Source: Espinal, C.A. & Matulić, D. (2019). Recirculating Aquaculture Technologies. Springer.

RAS is a modern system in which culture water is continuously treated and reused. The system generally includes mechanical filtration, biological filtration, aeration and disinfection nitrate. Additional units such as UV treatment, ozone and degassing systems may also be used.RAS is especially useful for ornamental fish culture because it provides better control over water quality and reduces water consumption.

Real-Time Water Quality Sensors

Modern sensors can continuously monitor important water quality parameters such as:

- Temperature
- pH
- Dissolved oxygen
- Ammonia and other nitrogen compounds
- Unlike traditional manual testing, real-time sensors can provide continuous information about changes in the culture water.

Internet of Things (IoT)

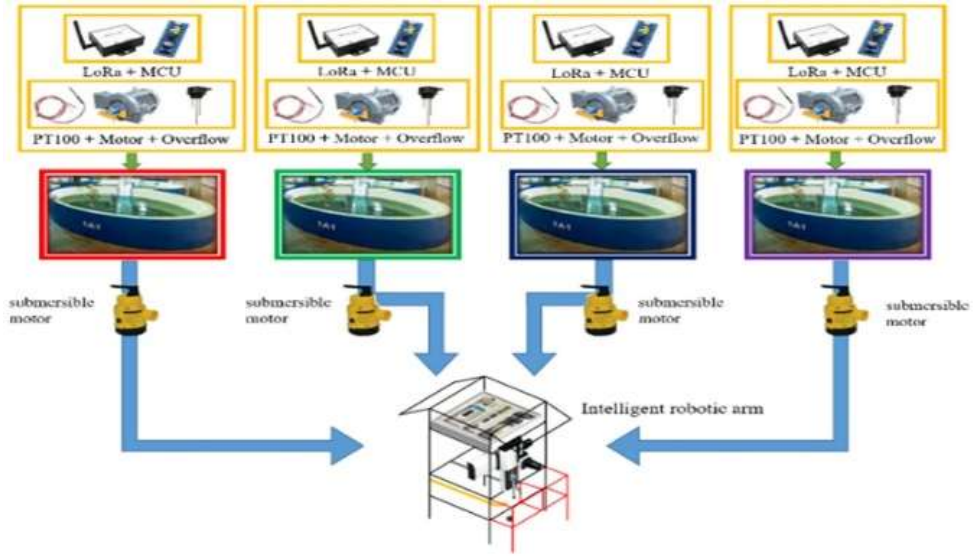


Figure 2. IoT-based real-time monitoring of water quality parameters.

Source: Shete, R.P., Bongale, A.M. & Dharrao, D. (2024). IoT Applications in Aquaculture.

IoT technology connects water quality sensors to a digital monitoring system. The sensors collection information from the culture tank and send it to a computer or mobile device. When a parameter goes outside the desired range, the system can provide an automatic alert or warning to the farmer. IoT-based monitoring can therefore reduce manual work and help in taking quick corrective action.

Artificial Intelligence (AI)

AI can be used to analyse large amounts of water quality data. It can identify patterns and support prediction of possible water quality problems.

- AI-based systems can help in:
- Predicting changes in water quality.
- Detecting abnormal conditions.
- Supporting automatic aeration.

- The combination of AI and sensor-based monitoring is an emerging approach for precision aquaculture .

Biofloc Technology

Biofloc technology uses beneficial microorganisms to convert nitrogenous waste into microbial biomass. and helps control ammonia and other waste compounds. Biofloc systems can reduce water exchange and improve nutrient recycling. However, proper aeration, pH, dissolved oxygen.

UV Sterilization

Ultraviolet (UV) treatment is used for water disinfection. Water passes through a UV chamber where ultraviolet radiation helps reduce microorganisms. UV treatment can be useful in ornamental fish systems because it helps improve biosecurity and reduces the microbial load in recirculated water. RAS commonly uses UV as one of the water treatment options.

Ozone Treatment

Ozone is a strong oxidizing agent used for water treatment. It can help control organic matter, colour and microorganisms in aquaculture water. Ozone treatment must be carefully controlled because excessive ozone can be harmful to fish. Therefore, proper dosage and system monitoring are important.

Advanced Biological Filtration

Biological filtration is essential for controlling toxic nitrogen compounds. Beneficial bacteria in the biofilter convert: Ammonia → Nitrite → Nitrate. This process is called nitrification. Modern biofilters provide a suitable surface for the growth of nitrifying bacteria and help maintain stable water quality.

Smart Water Quality Management System

An advanced ornamental fish farm can combine different technologies into one integrated system:. Culture Tank → Mechanical Filter → Biofilter → UV/Ozone → Sensor. Sensors continuously monitor water quality. The collected data can be sent through IoT to a mobile application or computer. If an abnormal value is detected, the system can activate equipment such as an aerator, pump or water treatment unit. This type of integrated system supports automatic and precision water quality management.

Advantages

- Advanced water quality technologies provide several benefits:
- Continuous monitoring of water quality.
- Early detection of dangerous changes.
- Better fish health and survival.
- Reduction in disease risk.
- Reduced water consumption.
- Less manual labour.
- Better control of intensive culture systems.
- Improved biosecurity.
- Efficient waste management.
- More sustainable ornamental fish production.

Challenges

Despite their advantages, advanced technologies also have some limitations. RAS and automated systems may require high initial investment, electricity and skilled operation. Sensors require regular calibration and maintenance to provide reliable measurements. Small-scale ornamental fish farmers may therefore need low-cost and simple technologies that are easy to operate and maintain.

Future Prospects

The future of ornamental fish culture is moving towards smart and precision aquaculture. Integration of RAS, IoT, AI, automated sensors, biofilters and advanced disinfection systems can provide better control of culture conditions. Future systems may combine real-time monitoring, automatic control and predictive technologies to detect water quality problems before they seriously affect the fish. Such integrated approaches can improve production efficiency while reducing water use and environmental impact.

Conclusion

Advanced water quality management technologies play an important role in successful ornamental fish culture. Technologies such as RAS, sensors, IoT, AI, biofloc, biological filtration, UV and ozone treatment can improve water quality and fish health. Proper selection and management of these technologies can support healthy, efficient and sustainable ornamental fish production.

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VEGETABLE GRAFTING: HARNESSING ROOTSTOCK–SCION SYNERGY FOR BETTER CROP PERFORMANCE

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Abstract

Grafting in vegetables has gained popularity relatively recently among vegetable farmers globally. Initially utilized to control soil-borne diseases, it remains crucial in modern intensive agriculture. Over time, with advancements in grafting techniques and related research, it has evolved into a versatile method employed for various purposes. Grafting serves as a key component of integrated pest management, helping to combat soil-borne pathogens and pests in solanaceous and cucurbitaceous crops by using appropriate rootstocks. Grafted seedlings are particularly favored in hydroponic systems due to the risk of rapid disease spread once plants are infected. Given the limited availability of fertile land and the high global demand for vegetables, cultivation often occurs in challenging soil and environmental conditions, such as thermal stress, drought, flooding, pollution from persistent organic chemicals, low soil temperature, and high soil salinity, especially in protected environments where continuous cropping is common. One effective strategy to mitigate production losses caused by these environmental stresses is to graft vegetables onto rootstocks that can enhance soil nutrient uptake, protect against soil-borne pathogens, and withstand adverse conditions. Vegetable grafting has also proven to be a safe method for producing organic and eco-friendly crops while reducing the absorption of harmful agricultural residues. Grafting may impact quality attributes like firmness, texture, flavor, and nutritional compounds by altering the movement of metabolites associated with fruit quality to the scion through the xylem or by modifying the scion's physiological processes.

Keywords: Vegetable grafting, rootstock, cucumber, eggplant, muskmelon

Vegetables

Grafting can be defined as the natural or deliberate fusion of plant parts so that vascular continuity is established between them and the resulting genetically composite organism functions as a single plant. Commercial vegetable grafting originated in Japan and Korea and was practiced for about 30 years. At first the cultivation of grafted plants in vegetables started to challenge the serious crop loss caused by infection of soil borne diseases aggravated by successive and intensive cropping. Even though grafting has been a mere common practice in fruit trees since ages, vegetable grafting is of recent popularization in a commercial scale.

As a result farmers frequently encounter various problems other than soil borne pathogens caused by successive as well as off-season cropping such as low temperatures during the winter, high humidity in the high tunnels, insufficient light intensity, and lack of well-balanced fertilization. The produces grown under these heavily stressed conditions frequently suffer from heavy incidence of soil-borne diseases, abnormal abiotic stresses which lead to physiological disorders, and quality deterioration. In addition to the widely recognized advantages of disease tolerance and high crop

yields through vigorous attainment of nutrients, grafting technology is also highly effective in ameliorating crop losses caused by adverse environmental conditions such as low soil temperature and high soil salts, especially under protected cultivations where successive cropping or continuous farming is routinely practiced. Grafted seedlings are much favored in hydroponics farming systems where the chances of rapid spread of noxious diseases, once infected, is high.

Grafting increases the yield and pro motes biotic/abiotic stress tolerance. Grafting is also used to induce tolerance to abiotic stresses viz. flooding, drought and salinity. In Japan (92%), Korea (98%) and China (20%), major share in watermelon production is from grafted seedlings. In Europe, Spain is leading in grafted seedlings production with 129 million grafted seedlings followed by Italy (47 million grafted seedlings) and France (28 million grafted seedlings) (FAO 2019). Grafting as a technology for the commercial production of vegetables was later on adopted by many countries in Europe, Middle East, Northern Africa, Central America and other parts of Asia. In India, grafting work has been started in IIHR Bangalore by Dr. RM Bhatt and his associates. Their work was on identification of rootstocks for waterlogged conditions. For this purpose, they have imported semiautomated grafting machine. IIHR Bangalore organized first ever short course on vegetable grafting during the year 2013. NBPGR regional station, Thrissur, Kerala have done work on Cucurbit grafting by taking *Momordica cochinchinensis*, a dioecious plant. The female plants were grafted on to the male plants to increase its production. Graft success was 98%. CSKHPKV, Palampur initiated work on grafting and identified more than 22 rootstocks of brinjal, chilli, tomato and cucurbits for importing resistance to bacterial wilt and nematodes. Some private players are also involved in grafting.

Importance of vegetable grafting

1. **Achieve soil borne disease resistances/tolerances:** Solanum torvum and pest was more resistant than *S. sisymbriifolium* to *V. dahliae*, when grown on both fumigated and Verticillium-infested soil. Hybrid squashes (*Cucurbita maxima Duchesne × Cucurbitamoschata Duchesne*) are widely used as melon rootstocks are highly resistant to fusarium wilt and tolerant to verticillium wilt, monosporascus sudden wilt, and gummy stem blight. *Cucurbita maxima* were highly resistant and resistant to *M. incognita* in soil infested with nematode.
2. **Increase vigor and yields:** Grafting eggplant onto interspecific eggplant hybrids, especially the *Solanum incanum (SI) ×Solanum melongena (SM)* with, has proved advantageous for eggplant production, because the high vigor and good rootstock/scion compatibility resulted in improved early and total yields, without apparently impairing fruit quality or composition. In tomato rootstock like *Efialto'*, '*Heman'* and '*Maxifort* increase the marketable yield and enhance the lycopene content. The average yield of melon (44%) and watermelon (84%) plants grafted on different Cucurbita hybrids (*C. maxima x C. moschata*) as rootstocks were much higher than the yields of the non-grafted plants
3. **Improving quality traits:** Flavor, pH, sugar, colour, carotenoid concentration, texture can be affected by type of rootstock used in watermelon. different rootstocks affect grafted cucumber quality characteristics such as fruit shape, skin and flesh colour and texture, skin smoothness, firmness, rind thickness, and soluble solids content.
4. **Effect of grafting on flowering and harvest:** Influence early flowering compared with other rootstocks, watermelon grafted onto bottle gourd causes early formation of female flower. Cucumber varieties grafted onto a squash interspecific hybrid rootstock inhibited flowering

5. **High and low temperature Tolerance**: Brinjal grafted on heat tolerant rootstock of brinjal seemed promising and resulted in prolonged growth stage and yield increase upto 10%. In low temperature cucurbit crops are not germinate so use of grafting for off season crop. Grafted watermelon seedlings under low temperature stress have higher antioxidants and antioxidative enzyme activities in leaves than self-rooted watermelon seedlings.

Methods of Vegetable Grafting

A number of grafting techniques are employed in fruit bearing vegetables. Tomato and eggplants are mostly grafted by cleft and tube grafting. Tongue approach is used in grafting cucurbitaceae especially for cucumber. Slant-cut grafting is easier and has recently become popular for watermelon and melon. This method was developed mainly for robotic grafting. These methods have been discussed as under:

1. **Cleft grafting**: The seeds of the rootstock are sown 5-7 days earlier than those of the scion. The stem of the scion (at four leaf stage) are cut at right angle with 2-3 leaves remaining on the stem. The rootstock (at the four to five leaf stage) are cut at right angles, with 2-3 leaves remaining on the stem. The stem of the scion is cut in a wedge, and the tapered end fitted into a cleft cut in the end of the root stock. The graft is then held firm with a plastic clip. Move the tray filled with grafted plants to proceed for healing up.
2. **Tube or Japanese Grafting**: This grafting has been developed for vegetable seedlings grown by plug culture. This method makes possible to graft small plants grown in plug trays two or three times faster than the conventional method. The smaller the plants, the more plants can be fitted into healing chambers or acclimation rooms. Cut rootstock under cotyledons in a 45° or sharper angle. Prepare the scion with matching hypocotyl width cut in the same angle at about 5- 10 mm below the cotyledons. Place one tube a half way down on top of the cut end of rootstock hypocotyl. Insert the scion into the grafting tube so that cut surface aligns perfectly with that of rootstock. Move the tray filled with grafted plants to proceed for healing up to 7 days.
3. **Tongue Approach Grafting**: In this method, seeds of cucumber are sown 10-13 days before grafting and pumpkin seeds 7-10 days before grafting, to ensure uniformity in the diameter of the hypocotyls of the scion and rootstock. The shoot apex of the rootstock is removed so that the shoot cannot grow. The hypocotyls of the scion and rootstock are cut in such a way that they tongue into each other and the graft is secured with a plastic clip. The hypocotyl of the scion is left to heal for 3-4 days and then crushed between the fingers. The hypocotyl is cut off with the razor blade three or four days after being crushed.
4. **Slant-Cut Grafting:** This grafting technique is easy to practice and has become popular. This method is mainly developed for robotic grafting. It is important to remove the 1st leaf and lateral buds when a cotyledon of rootstock is cut on a slant.

Scion plant	Rootstock	Methods
Eggplant	*Solanum torvum, S. sissymbrifolium, Solanum khasianum*	Tongue and cleft method. Cleft method Both tongue and cleft methods
Tomato	*L. pimpinellifolium, S. nigrum*	Only Cleft method Tongue and cleft methods
Cucumber	*C. moschata, Cucurbita maxima*	Hole insertion and tongue method tongue method

Scion plant	Rootstock	Methods
Water melon	*Benincasa hispida, C. moschata, C. melo, C. moschata × C. maxima, Lagenaria siceraria*	Hole insertion and cleft method Hole insertion and cleft method Cleft method Hole insertion method Splice Grafting
Bitter gourd	*C. moschata, Lagenaria siceraria*	Hole insertion and tongue method Hole insertion

Problems confronted during vegetable grafting

Various problems associated with the production and management of grafted transplants is as following:

a) This technique is labour intensive and required specialized trained workers.

b) Requires time management for rootstock and scion seeds sowing.

c) Require a controlled environment for graft healing.

d) Grafting can increase the risk of pathogen spread, especially for seed borne pathogens in the nursery. Workers performing grafting within a greenhouse and growth chamber face the problems of heat stress and discomfort, especially during April-June, September and October

Conclusion

The technique of vegetable grafting has beneficial impacts on the growth of plants when different types of rootstocks are used, especially seen in the size of fruits, notably in crops like watermelon, cucumber, and tomato. The shape of the fruit is mainly determined by the genetic makeup of the scion. The effects of grafting on the thickness of the outer and inner layers of the fruit are not as significant as those influenced by the scion's genes and are also influenced by when the fruit matures. The color of the skin and flesh of fruits each year, which is dependent on the levels of pigments, can be affected by grafting directly and indirectly, especially in how it interacts with the process of fruit ripening. This interaction is often observed in watermelons, whereas the impact of coloration on tomatoes, melons, and peppers is strongly linked to the specific rootstock used. With the wide range of uses for vegetable grafting around the world, this method has the potential to address challenges faced by the vegetable industry in India. It could help increase farmers' earnings by enhancing crop production, thus reducing expenses on purchasing large quantities of fertilizers, pesticides, and disease control products.

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THE SEED OF TOMORROW: SMART COATINGS FOR SUSTAINABLE AND CLIMATE-RESILIENT AGRICULTURE

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Abstract
Climate change and increasing environmental stresses are making successful seed germination and early seedling establishment more challenging. Smart seed coating is emerging as a promising value-added technology that goes beyond conventional seed protection by creating a functional interface between the seed and its surrounding environment. Smart coatings can incorporate biopolymers, hydrogels, beneficial microorganisms, micronutrients, biostimulants, enzymes and nano-enabled materials to regulate moisture, improve nutrient availability, support plant growth and enhance stress tolerance. Controlled- and stimuli-responsive release systems can further deliver active ingredients when and where they are needed. These advances are transforming seed coating from a simple protective treatment into a precision seed-enhancement technology. Although challenges related to compatibility, storage stability, field performance, cost and environmental safety remain, smart seed coating offers considerable potential for improving crop establishment, resource-use efficiency and climate resilience, contributing to more sustainable agriculture.

Keywords: Smart seed coating, Biopolymers, Nanotechnology, Climate resilience, Sustainable agriculture

Introduction

Seeds are the foundation of crop production and the first step in the food chain. Their quality strongly influences germination, crop establishment, uniformity and final productivity. However, changing climatic conditions such as drought, high temperature, salinity, irregular rainfall, poor soil conditions and emerging pests and diseases can seriously affect seed germination and early seedling growth. Even high-quality seeds with good vigour may perform poorly when environmental conditions are unfavourable. Therefore, improving seed performance and tolerance to stress during germination and early growth has become an important goal of modern seed science. These challenges have encouraged the development of advanced seed enhancement technologies, including smart seed coating. Unlike conventional coatings that mainly deliver protectants, nutrients, or other materials, smart coatings are designed to provide a more controlled and targeted supply of beneficial inputs. They can incorporate hydrogels, biopolymers, nanomaterials, microorganisms, nutrients and biostimulants to create a favourable microenvironment around the seed (Yazhini *et al*., 2024).

The basic idea is to transform the seed surface from a simple carrier of treatment materials into a functional interface that supports seed establishment. Smart coatings can be designed to respond to environmental conditions such as moisture, pH or temperature and regulate the release of active ingredients accordingly. For example, hydrogels can help retain water, nutrient-based coatings can provide localized nutrition, microbial coatings can support beneficial microorganisms, and

responsive materials can control the release of specific compounds. Thus, smart seed coating represents a shift from simply treating the seed to engineering the seed environment for better and more efficient establishment under changing conditions.

What can be put into a smart seed coating?

Hydrogels – Helping seeds manage water

Water availability is critical for seed germination and early seedling establishment, especially in rainfed and drought-prone areas. Smart coatings containing hydrophilic polymers or hydrogels can absorb and retain water around the seed, helping maintain moisture during early growth. However, excessive water retention may reduce oxygen availability and disturb normal germination. Therefore, an effective hydrogel coating should maintain a balance between water retention, oxygen supply, seed hydration and coating degradation.

Biopolymer- Building an eco-friendly coating

Biopolymers are gaining attention as useful materials for smart seed coatings because they can form a protective layer on the seed while remaining biodegradable (Sprey *et al*., 2025). Materials such as alginate, chitosan, cellulose, starch, pectin and gum arabica can help improve coating strength, retain moisture and control the release of nutrients or beneficial microorganisms. Since they are derived from natural sources, biopolymers also offer a more sustainable alternative to some synthetic coating materials. Increasingly, agricultural residues and other renewable resources are being explored as raw materials for these coatings. However, their effectiveness, consistency and behaviour under field conditions still need to be carefully evaluated before wider use.

Microbial seed coatings – Bringing beneficial microbes to the seed

Beneficial microorganisms are becoming an important part of smart seed coatings because coating places them directly on the seed, close to the emerging root. Microbes such as *Bacillus*, *Pseudomonas*, *Rhizobium*, *Trichoderma* and arbuscular mycorrhizal fungi can promote root growth, improve nutrient availability, suppress pathogens and help plants cope with environmental stress (Kohl *et al*., 2025). Combining compatible microorganisms as microbial consortia can further provide multiple complementary benefits, making microbial seed coatings a promising approach for sustainable crop establishment.

Nanotechnology – Nanomaterials with new possibilities

Nano-smart seed coating is an advanced seed enhancement technology that integrates nanomaterials into a thin, functional coating to regulate the seed–environment interface and improve early plant establishment. Nanomaterials such as zinc oxide, titanium dioxide, silver, graphene oxide, carbon nanotubes and chitosan nanoparticles offer unique surface, chemical and biological properties. Their incorporation can enhance water absorption, oxygen exchange, nutrient uptake and seed germination while providing controlled delivery of nutrients, growth regulators and beneficial compounds. Nano-smart coatings can also provide antimicrobial protection against seed- and soil-borne pathogens and improve tolerance to drought, salinity and temperature stresses, thereby supporting uniform emergence, vigorous seedlings and more sustainable crop production.

Microencapsulation: Protecting beneficial microbes

Microencapsulation helps improve the survival of beneficial microorganisms in seed coatings by enclosing them within a protective polymeric matrix. This protects microbial cells from environmental stresses during storage and allows their gradual release after sowing. It is

particularly useful for sensitive microbes and demonstrates how smart seed coating combines microbiology, polymer science and seed technology to maintain microbial viability and improve their interaction with developing seedlings.

Stimuli-responsive coatings – Coatings that respond to the environment

Stimuli-responsive coatings represent an advanced approach in smart seed technology, where the coating responds to environmental signals such as moisture, pH, temperature or light. These signals can control the swelling, degradation or permeability of the coating and regulate the release of nutrients, biostimulants or protective compounds. For example, a moisture-responsive coating can adjust its behaviour according to water availability, providing more controlled delivery under changing soil conditions. Thus, the environment acts as a trigger, making seed treatment more precise and efficient.

Enzyme-based seed coatings – An emerging frontier

Enzymes are emerging as another promising component of smart seed coatings. Recent research has explored amidohydrolases and phosphatases in wheat seed coatings, showing improvements in seedling vigour, root growth, biomass and phosphorus uptake under experimental conditions (Ortega *et al*., 2026). Unlike coatings that simply supply nutrients, enzyme-based coatings may help improve nutrient availability and modify biochemical processes around the developing seedling. This approach could eventually link smart seed coating with rhizosphere engineering, where the coating helps create a favourable biochemical environment around the emerging root.

Smart nutrient coating -Delivering nutrients when seeds need them

Smart seed coatings can provide nutrients such as zinc, iron and phosphorus directly around the seed and developing root, reducing nutrient loss and improving early nutrient availability. However, the dose must be carefully optimized because excessive nutrient concentrations can create osmotic stress and reduce germination. Therefore, effective nutrient coatings aim to deliver the right nutrient, at the right dose, in the right place and at the right time for better seedling establishment.

Smart protection coatings – Targeting pathogens where protection is needed

Seed- and soil-borne pathogens can seriously affect crop establishment. Smart coatings can provide localized and controlled delivery of fungicides, biopesticides or beneficial microorganisms around the seed and emerging root, potentially reducing unnecessary chemical use. Beneficial microbes such as *Trichoderma*, *Bacillus* and *Pseudomonas* can suppress pathogens through competition, antibiosis and other mechanisms. Future coatings may combine microbes, nutrients and biostimulants in biodegradable matrices, although their compatibility, effectiveness and environmental safety require careful evaluation.

Smart Coatings and Climate Resilience

Climate stresses such as drought, salinity and high temperature can severely affect germination and early seedling growth. Smart seed coatings can address these challenges by combining multiple functions in a single treatment. Hydrogels can retain moisture, beneficial microorganisms can promote root growth and protection, micronutrients can support metabolism, biostimulants can improve stress responses, and biopolymers or nano-enabled materials can provide controlled delivery. Thus, multifunctional coatings can help strengthen seedlings during their most vulnerable stages and offer a promising approach for improving crop establishment under changing climatic conditions.

The Indian perspective: From research to field application

Smart seed coating is gradually moving from laboratory research towards field-level validation in India. A notable recent development from ICAR–Indian Institute of Oilseeds Research (ICAR-IIOR), Hyderabad, is a biopolymer-based multifunctional multilayer coating designed to deliver beneficial microorganisms, biostimulants, micronutrients and reduced-dose crop-protection inputs through controlled release. The technology has been demonstrated in groundnut under farmers' field conditions. All India Coordinated Research Project on Seed (AICRP-Seed) trials reported productivity gains of 12% to 37% over untreated seeds, while Telangana trials showed nearly 30% higher yields in groundnut and soybean. These results represent field demonstrations rather than a universal yield advantage, but they indicate the potential of multifunctional coatings under practical conditions. The development highlights an important transition in Indian seed technology: concept → formulation → field demonstration → potential commercialization. For wider adoption, further validation across crops and environments, along with attention to cost, storage stability, application methods, regulatory requirements and farmer acceptance, will be essential.

From smart coating to precision seed technology

The future of smart seed coating is likely to move towards precision seed enhancement, where the coating is designed according to the specific crop, genotype, soil, climate and target stress. For example, drought-prone areas may require water-retaining materials combined with stress-tolerant microorganisms, while saline soils may benefit from salt-tolerant microbes and targeted nutrient delivery. Disease-prone soils could receive coatings containing compatible biological control agents and protective compounds.

This next generation of seed technology could integrate microbiome science, omics, artificial intelligence, nanotechnology and materials science. Microbiome analysis may help identify suitable microbial partners, while omics can reveal how coated seeds respond to different stresses. AI could assist in predicting suitable combinations of polymers, microorganisms, nutrients and release rates for specific conditions. Together, these technologies could shift seed treatment from a one-formulation-fits-all approach towards customized seed enhancement, where the coating is developed to meet the needs of a particular crop–soil–environment combination.

Challenges before smart Seeds become mainstream

Smart seed coating has strong potential, but moving from an innovative laboratory concept to a reliable, affordable and farmer-ready technology requires overcoming several challenges.

1. Component compatibility- A smart coating may contain polymers, microorganisms, nutrients, biostimulants and protective chemicals. These components can interact with each other and may reduce microbial survival, alter release behaviour or affect seed quality.

2. Seed safety - An effective coating should improve seed performance without interfering with imbibition, respiration, oxygen movement or germination**.** Excessive coating thickness, moisture retention or high concentrations of active ingredients may adversely affect seed establishment.

3. Storage stability- The effectiveness of a coating should not disappear during storage. Microorganisms, enzymes and other sensitive biological components may lose viability or activity over time.

4. Field performance- A formulation that performs well under controlled conditions may behave differently in farmers' fields because of variations in soil type, pH, temperature, moisture, rainfall,

nutrients and indigenous microbial communities. Multi-location and multi-season testing are therefore essential.

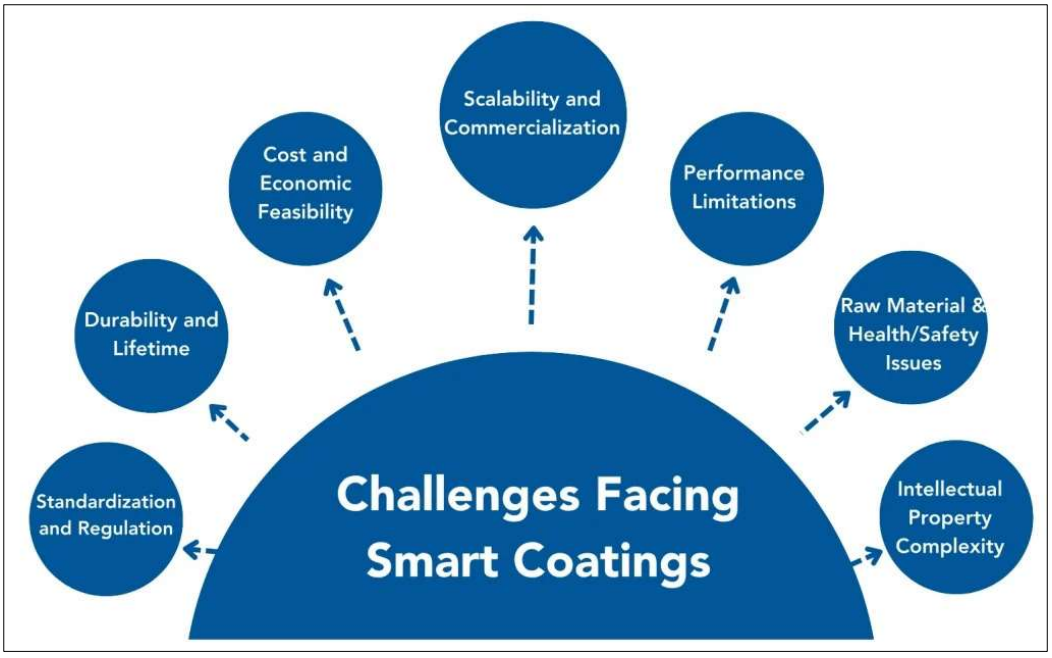
5. Cost and scalability- Encapsulation, multilayer coatings, nanomaterials and specialized polymers can increase production costs. For widespread adoption, smart coatings must be technically effective, commercially scalable and economically attractive to farmers.

6. Environmental safety- The long-term behaviour of coating materials, particularly novel and nano-enabled materials, requires careful assessment. Their degradation, persistence, effects on beneficial soil microorganisms and potential environmental impacts must be understood before large-scale use.

7. Regulatory challenges- Products combining microorganisms, pesticides, nutrients, biostimulants or novel materials may involve different regulatory requirements. Clear guidelines for product safety, efficacy, quality control and environmental impact will be important for commercialization.

8. Crop- and environment-specific performance

No single formulation may be suitable for every crop and growing condition. The performance of a smart coating can depend on the seed genotype, soil environment, climate and target stress. Future formulations therefore need greater precision and customization.



What does the future seed look like?

The future seed could act as a miniature biological delivery system, with a coating designed for its specific environment.

- Hydrogel: Retains moisture
- Microbes: Promote growth and protection
- Micronutrients: Provide targeted nutrition
- Biostimulants: Improve stress tolerance
- Responsive materials: Control release when needed
- Biopolymers: Provide protection and biodegradability

Thus, seed technology may move from “one coating for all” to precision coatings designed for a specific crop, soil, climate and stress.

Conclusion

Smart seed coating is evolving from a simple protective layer into a multifunctional interface between the seed and its environment. By integrating biopolymers, hydrogels, beneficial microorganisms, nutrients, enzymes and responsive materials, it can support moisture management, nutrition, protection and stress tolerance.

The future of smart coating is not about adding more components, but delivering the right input, at the right dose, place and time. With improved field validation, affordability, safety and sustainability, smart seed coating could become an important tool for climate-resilient and precision seed technology.

"The future of climate-resilient agriculture may begin not in the field, but on the surface of the seed."

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WHAT'S ON THE MENU FOR COMMON CARP? EXPLORING ITS FEEDING HABITS IN LAKES, RIVERS AND WETLANDS

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Abstract
Common carp (*Cyprinus carpio*) is one of the most important freshwater fish, capable of wide-range of feeding spectrum. This reviewed showed that *C. carpio* has a highly flexible, feeds on phytoplankton, zooplankton, molluscs, benthic organisms, insects, and detritus. The proportion of plant- versus animal-based food items can differ dramatically between habitats and seasons, usually reflecting the availability of localized food resources. Other bottom-associated food materials, such as detritus are especially important in many ecosystems. In summary, *C. carpio* is characterized as flexible, bottom feeding omnivore with a detritivorous feeding habits. This dietary plasticity allows it to benefit from various food sources and eventually aids in its establishment in freshwater ecosystems all around the globe.

Keywords: Common carp, food and feeding, zooplankton, phytoplankton and detritus.

Introduction

Common carp (*Cyprinus carpio* Linnaeus, 1758) is a large-bodied cyprinid fish, which is regarded to be the world's most prevalent and ecologically detrimental invasion in freshwaters. In India, it was first imported in 1939 from then Ceylon and was transplanted in Nilgiri. However, another variety (scale carp) was brought from Bangkok to Cuttack (Orissa) in 1957 for aquaculture. The Bangkok strain of common carp (*C. carpio* var. *communis*) is widely used under aquaculture in plains while mirror carp (*C. carpio* var. *specularis*) and leather carp (*C. carpio* var. *nudus*) are used for aquaculture in upland waters of hill states (Das *et al*., 2023). Since its introduction in the late 1930s, it has established populations in rivers, reservoirs, lakes, wetlands, and floodplain ecosystems. Aquaculture was the main pathways for *C. carpio* introduction globally (Dwivedi *et al*., 2014). Freshwater ecosystems are the most affected by the exotic/alien fish invasion (Alam *et al*., 2026) as well as compete with indigenous species for breeding, space and feeding items (Tiwari *et al*., 2026). It's feeding plasticity and omnivorous habit enable it to thrive in diverse environmental conditions. Fishes feed on a wide range of plant and animal items as well as their parts and sand and mud, categorized by their diet type and feeding behaviour. Feeding behaviour of fishes is a strong ecological indicator that shows tolerance potential of fish, and functioning and health of water bodies.

Because of its plasticity, fast-growth and capacity to withstand a broad range of environmental conditions, common carp (*Cyprinus carpio*) are both an important aquaculture species and successful non-native fish in many freshwater systems. It has remarkable successfully invaded major freshwater bodies around the globe largely due to its feeding flexibility. Unlike many other fishes, common carp are not limited to a single food type. It is abroad spectrum feeder, eating anything

from microscopic organisms, leaves and plants, insects, molluscs, e.g., into very small or even tiny creatures. In simple terms, common carp is not a fussy feeder.

What Does Common Carp Eat?

Common carp is characterized as omnivore but its diet varies depending on the environment it lives in. Previous studies on gut content in common carp have reported phytoplankton, zooplankton, aquatic plants and larger debris (insects, molluscs), benthic organisms and detritus. Detritus and other bottom-associated materials that make up a significant portion of many waters' bodies constitutes its diet.

This study summarizes the feeding preferences of common carp inhabiting freshwater open water bodies of India and other parts of the world (Table 1 and Fig. 1). Gül *et al*., (2010) was observed that the zooplankton, phytoplankton and detritus form the main food items in the gut content of *C. carpio* in Hirfanli dam lake, Türkiye. Manon and Hossain (2011) estimated plants parts, phytoplankton and debris and detritus in proportion of 20.12%, 16.46% and 19.69% in the gut content of the *C. carpio* from the River Padma, Rajshahi, Northwestern Bangladesh. Mangi and Memon (2017) recorded aquatic plants (24%) and phytoplankton (31.41%) were consumed by *C. carpio* in district Larkana, Sindh, Pakistan, while detritus (39.8%), insects (36.4%) and macrophytes (12.4%) were reported in Lake Koka, Ethiopia by Dadebo *et al.* (2015). In most recent studied, Qadir *et al* (2024) stated that the *C. carpio* feed mainly on plants (54.50%), animals (34.65%) in the Dal-Lake, Kashmir, India. Ayalew *et al*. (2025) estimated that the zooplankton (36.27%) and phytoplankton (31.41%) appeared in the gut content of *C. carpio* from the Lake Ardibo, Ethiopia.

Table 1. Diet composition of *C. carpio* reported by earlier workers in different climatic conditions.

Area in which work was carried out	Food and Feeding habits	Researchers
Lake Ardibo, Ethiopia	Zooplankton, phytoplankton, macrophyte, detritus (omnivorous).	Ayalew *et al*., 2025
Arunachal Pradesh, India	Algae, zooplankton, benthic organisms, plant residues muddy substratum (Omnivorous).	Saikia and Das (2008)
Hirfanli Dam, Turkey	Phyto and zooplankton, and benthic organisms (Omnivorous).	Ali *et al*., 2010
Naogaon district, Bangladesh	Parts of aquatic plant, phyto and zoo plankton, debris and detritus, insects and semi-digested materials (Omnivorous).	Manon and Hossain 2011
Dal Lake of Kashmir valley	Detritus, plant and animal matter, (detri-omnivore).	Naik *et al*., 2015
Ganga river Prayagraj waters	Detritus, molluscs, phyto and zooplankton, insects, macrophytes and annelid worm (detri- omnivorous).	Das *et al*., 2023
District Larkana, Sindh, Pakistan	Aquatic plants, molluscs, insects, sand, mud, debris (Omnivorous).	Mangi and Memon 2017
Dal-Lake, from Kashmir, India	Macrophytes, crustaceans, diatoms, green algae, bluegreen algae, rotifera, protozoans, oligochaetes (illiophagic omnivore).	Qadir *et al*., 2024

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Why Do They Feed Near the Bottom?

Common carp has a protrusible mouth with sensory barbels that aid it in locating food. It can disturb soft sediments while feeding and search for buried or near-bottom organisms and organic matter. This behaviour enables it to access detritus, benthic invertebrates, molluscs and insect larvae and other food sources that are not readily available for many fishes. Therefore, describing common carp simply as an "omnivorous fish" does not tell the whole story. In many freshwater ecosystems, it is more appropriately described as a bottom-feeding, detritus-associated omnivore.

Overall, the study highlights that common carp is primarily a bottom-feeding detritivorous-omnivorous species, with detritus forming the major dietary component, supplemented by benthic invertebrates, plankton, aquatic macrophytes, insects, and organic debris. Seasonal changes, habitat characteristics, and fish size influence dietary composition. The species is an omnivorous benthic feeder with a strong preference for bottom-associated food organisms. It feeds by rooting through soft sediments using its protrusible mouth and sensitive barbels. This feeding behaviour allows it to exploit a wide range of food resources depending on their availability in the ecosystems. Evidence from Indian open water ecosystems indicates that common carp is predominantly a detritivorous-omnivorous bottom feeder. Detritus consistently forms the largest proportion of its diet, followed by molluscs, phytoplankton, zooplankton, aquatic macrophytes, insects, and annelids. This species exhibits considerable dietary flexibility, allowing it to adapt successfully to rivers, reservoirs, lakes, and wetlands across India. This adaptability contributes to its successful establishment but also necessitates careful management because of its potential ecological impacts on native fish communities.

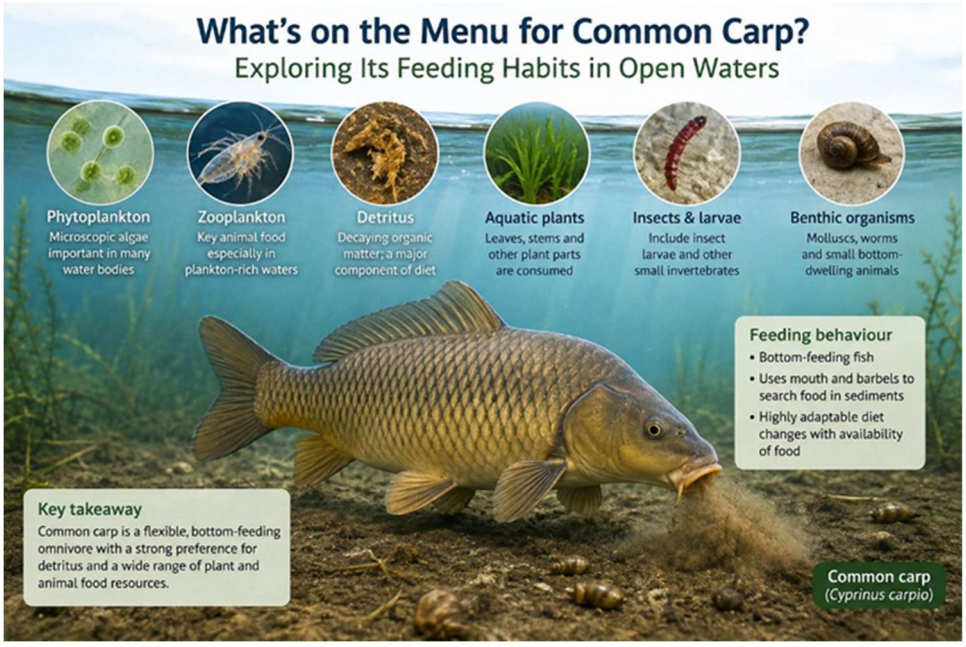


Figure.1 Feeding habits of *C. carpio*

Conclusion

It may be concluded that the *C. carpio* appears to feed in an omnivorous manner. However, the proportions of dietary elements found in its gut content differ between studies because of different habitat conditions, seasonal food availability and methods used to analyse diet. Overall, omnivorous feeding trait in *C. carpio* is recorded for both temperate and tropical environmental conditions.

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FCJ-11: A PROMISING FCV TOBACCO VARIETY FOR NORTHERN LIGHT SOILS REGION

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Abstract
Tobacco is an important commercial crop contributing significantly to the agricultural economy, export earnings and livelihoods of tobacco growing farmers in India. However, FCJ-11, developed by ICAR-National Institute for Research on Commercial Agriculture (ICAR-NIRCA), is gaining acceptance among tobacco growers in the Northern Light Soils region of Andhra Pradesh. Front Line Demonstrations covering 176 acres during 2024-25 and 179 acres during 2025-26 assessed its performance under farmers' field conditions. The variety showed good plant growth, higher stem girth, thicker midrib, desirable leaf thickness, uniform maturity and satisfactory curing performance with attractive cured-leaf colour. Comparatively lower pest and disease incidence and encouraging performance under efficient nutrient management were also observed. Continued cultivation over successive seasons reflects growing farmer confidence and acceptance. Overall, FCJ-11 has potential for quality oriented, resource efficient and economically viable FCV tobacco production in suitable areas of Andhra Pradesh.

Keywords: Efficient, FCJ-11, farmer adoption, tobacco, leaf quality

Introduction

Flue Cured Virginia (FCV) tobacco is an important commercial crop in India, particularly in Andhra Pradesh and Karnataka, contributing to farm income, rural employment and export earnings. The productivity and profitability of FCV tobacco depend not only on crop management but also on the selection of varieties suited to specific soil and climatic conditions. With increasing production costs, labour constraints, climatic variability and changing quality requirements, farmers need varieties that combine stable crop performance with desirable leaf quality and efficient resource use. In this context, In the Northern Light Soils region of Andhra Pradesh, particularly in the tobacco growing areas of East Godavari, West Godavari and Eluru districts, the Flue-Cured Virginia (FCV) tobacco variety FCJ-11, developed by the ICAR-National Institute for Research on Commercial Agriculture (ICAR-NIRCA), is gaining escalating attention among the tobacco growers. The variety has shown encouraging performance in farmer's fields, with desirable leaf quality, comparatively stable crop performance, satisfactory curing characteristics and good market prospects.



For commercial tobacco growers, varietal selection is an important determinant of productivity, quality and profitability. Farmers require varieties that can perform consistently under field conditions, respond well to recommended management practices, withstand pest and disease incidence, use production inputs efficiently and produce leaves suitable for commercial grading. The field experience with FCJ-11 indicates that the variety possesses several characteristics relevant to these requirements. Its growing area under cultivation, together with continued use by farmers across successive seasons, reflects the practical value being observed in the field.

FCJ-11 from Research to Farmers Fields

With the objective of making improved tobacco varieties available to farmers, ICAR-NIRCA scientists have been promoting FCJ-11 through seed and seedling distribution, field demonstrations, farmer interactions and technical guidance. FCJ-11 seed and seedlings were distributed to farmers in several tobacco growing villages of Andhra Pradesh. Its performance has been systematically observed under farmers field conditions through Front Line Demonstrations (FLDs). Demonstrations covering 176 acres during 2024-25 and 179 acres during 2025-26 provided an opportunity to evaluate the variety under different field situations. These demonstrations also enabled scientists to collect direct feedback from growers regarding crop establishment, plant growth, harvesting, curing and market acceptance. An important feature of the programme has been the continued cultivation of FCJ-11 by several farmers. While some growers began cultivating the variety during its testing stage, others have continued with it for the second, third and fourth consecutive years. Such repeated cultivation provides useful field level evidence regarding the consistency and practicality of the variety.

Field Visits Strengthening Research - Farmer Linkages

To assess the performance of FCJ-11 and understand farmer's experiences, multidisciplinary teams from ICAR-NIRCA undertook field visits to important tobacco growing regions. Scientists interacted directly with growers cultivating the variety under diverse agro-climatic conditions. Discussions covered crop establishment, growth behaviour, leaf development, harvesting, curing performance, quality characteristics and market response. These interactions provided an opportunity to understand about the variety performance beyond experimental conditions.



Desirable Leaf Quality and Uniformity

FCJ-11 plants exhibit a relatively higher stem girth, indicating good stem strength and robust crop growth under field conditions. The leaves are characterized by a comparatively thicker midrib, providing good structural support to the leaf lamina. One of the important features reported by farmers is the desirable quality and relatively uniform appearance of FCJ-11 leaves. In FCV tobacco, yield alone does not determine the commercial value of the crop. Leaf size, thickness, texture, colour, maturity, uniformity, curing response and other quality characteristics influence grading and market acceptance. Farmers cultivating FCJ-11 in different villages observed relatively uniformity in leaf size and maturity. They also reported desirable leaf thickness, softness and physical uniformity.

Uniform Maturity and Harvest Management

The relatively uniform maturity of FCJ-11 was another practical advantage highlighted by growers. Tobacco harvesting is labour-intensive, and farmers often face difficulty in arranging adequate labour within the required harvesting window. When leaves mature more uniformly, harvesting can be completed within a shorter period and labour can be organized more efficiently. Farmers reported that the synchronized maturity of leaves helped them complete harvesting operations more quickly. It also facilitated better planning of curing activities. This characteristic is particularly useful in areas where labour availability is limited. Better coordination between harvesting and curing can diminishes operational delays and may help lower labour expenditure. Thus, the maturity pattern of FCJ-11 provides a practical advantage in crop and labour management in addition to its contribution to leaf uniformity.

Curing Performance and Marketability

Curing is a significant stage in FCV tobacco production because it strongly influences the final appearance and quality of the cured leaf. Farmers reported satisfactory curing performance of FCJ-11 and desirable colour development following curing. The combination of colour, thickness, texture and uniformity was viewed positively during field interactions. Better uniformity allows leaves to be handled and segregated more efficiently during post-harvest operations. Since tobacco marketing is strongly influenced by cured-leaf quality and grade, these characteristics can contribute to better market opportunities.



Lower Pest and Disease Pressure

Another favourable field observation associated with FCJ-11 was its comparatively lower susceptibility to major pests and diseases. Farmers reported that lower pest and disease pressure reduced the need for frequent plant protection interventions in their fields. This can aid in decreases the expenditure on pesticides and other crop protection inputs while enhancing the crop reliability.

Efficient Fertilizer Use: An Emerging Advantage

A further encouraging observation from farmers fields is the ability of FCJ-11 to produce good crop performance under comparatively lower fertilizer application levels when recommended agronomic practices are followed. This suggests potential for efficient nutrient utilization by the variety.

A Variety Suited to Changing Production Conditions

Tobacco farmers are currently dealing with several challenges, including changing weather patterns, increasing cultivation costs, labour shortages, pest and disease risks and evolving market requirements. These challenges increase the importance of varieties that combine productivity with quality and efficient resource use. FCJ-11 has shown encouraging field-level characteristics in this context.

Scientist Farmer Interaction as a Key to Technology Adoption The experience with FCJ-11 demonstrates that varietal promotion is most effective when supported by continuous farmer interaction. ICAR-NIRCA's field activities have included seed and seedling distribution, Front Line

Demonstrations, field monitoring, farmer meetings and on-site technical guidance. Scientists provided recommendations relating to crop management, water use, nutrient management, pest and disease management and curing. Farmers in turn, provided direct feedback on the performance of the variety and the problems encountered during cultivation.



Scope for Wider Evaluation and Adoption

The field performance of FCJ-11 across several locations provides encouraging evidence for its continued evaluation in suitable tobacco-growing areas of Andhra Pradesh. The observations from farmers' fields indicate relatively stable crop growth under different soil and climatic conditions. However, continued demonstrations across locations and seasons are important to further assess yield stability, leaf quality, nutrient use efficiency, pest and disease response, curing behaviour and economic performance.

Conclusion

FCJ-11 is emerging as a promising FCV tobacco variety in the Northern Light Soils region of Andhra Pradesh. The experience also demonstrates the importance of maintaining a strong connection between research and farmers. Seed distribution, field demonstrations, continuous monitoring, direct interaction and technical guidance have enabled scientists and growers to jointly assess the variety under diverse field conditions. With continued evaluation and appropriate agronomic management, FCJ-11 has considerable potential to contribute to quality oriented, resource efficient and economically viable FCV tobacco production in suitable regions of Andhra Pradesh. Its field journey demonstrates a simple but important principle: the value of agricultural research is ultimately realized when improved technologies perform effectively under farmers' conditions and address their practical production needs.

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MICRORNAS: TINY MOLECULES MAKING A BIG IMPACT ON AGRICULTURE

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Introduction

MicroRNAs (miRNAs) are small, non-coding RNA molecules that function as key post-transcriptional regulators of gene expression in plants. They participate in different biological processes, including growth and developmental transitions, nutrient homeostasis, flowering, and seed development. Additionally, miRNAs contribute to plant defense against pathogens and to tolerance of abiotic stresses such as drought, heat, and salinity, primarily through sequence-specific mRNA cleavage or translational repression of target transcripts. This regulatory activity enables crop plants to modulate gene expression in response to developmental and environmental cues, thereby enhancing stress resilience and physiological efficiency. Consequently, miRNAs are increasingly being explored as targets for crop improvement, including approaches such as miRNA overexpression, target mimicry, and genome editing, to develop crop varieties with improved stress tolerance and agronomic performance.

What Are miRNAs and Their Biogenesis?

MicroRNAs are short, single-stranded non-coding RNA molecules typically 20–24 nucleotides in length. Unlike messenger RNA (mRNA), which carries instructions from DNA to produce proteins, miRNAs do not code for proteins. Instead, they play a regulatory role by binding to specific mRNAs and preventing them from being translated into proteins. This process, known as post-transcriptional gene regulation, is essential for maintaining cellular balance. In the plant cell nucleus, a gene is first copied into a long RNA strand called pri-miRNA. The proteins DCL1, HYL1, and SE trim this into a short miRNA duplex, which is stabilized and exported into the cytoplasm. One miRNA strand of the duplex incorporates into the Argonaute (AGO) protein to form the RISC complex, generating the active mature miRNA. This miRNA then silences its target genes by blocking the target mRNA translation into protein, triggering its breakdown or translational repression (Warkad et al., 2025).

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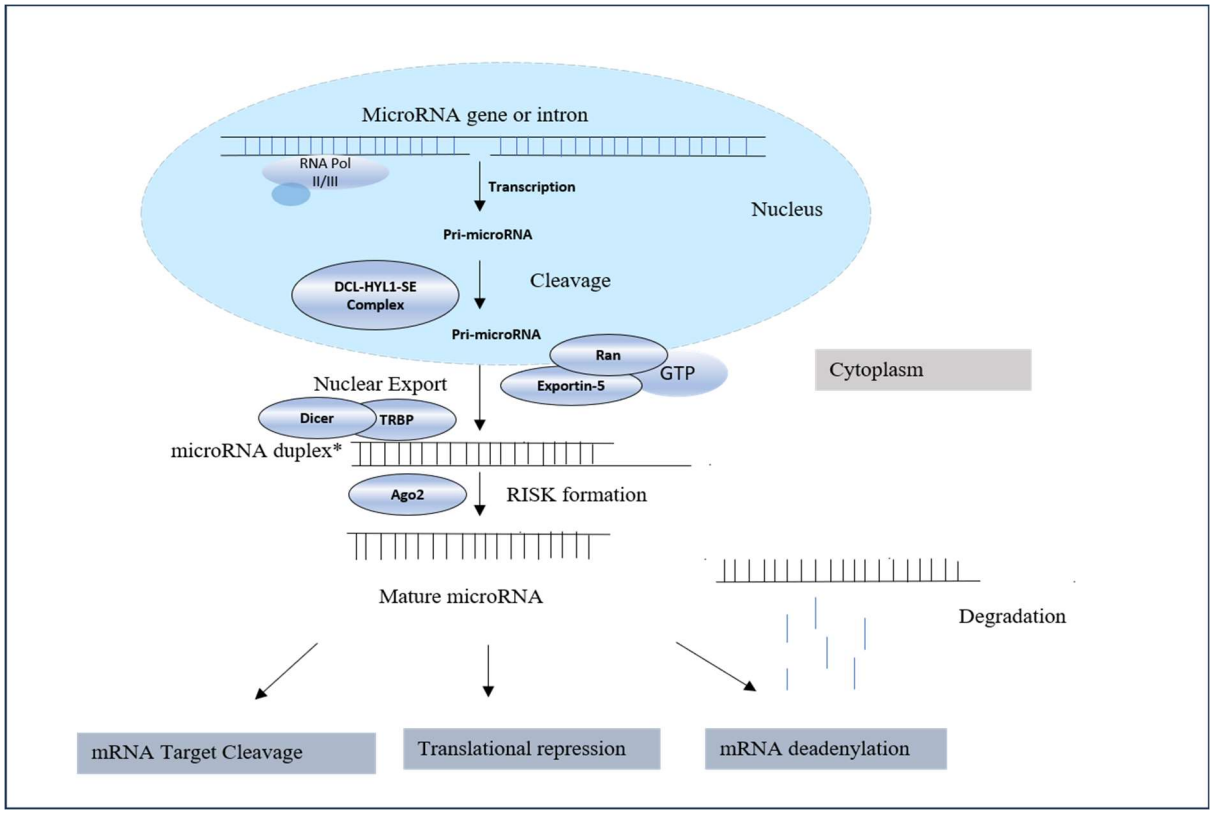


Fig. 1. Biogenesis of microRNA (miRNA) in plants

The Role of miRNAs in Agriculture

Agricultural research is not just about maximizing yield; it's also about developing climate-resilient crops with additional nutritional value. That's where miRNAs come into play in their functional role. Studies have shown that specific miRNAs respond actively to abiotic stresses like drought, extreme temperatures, and soil salinity. They also play a role in biotic stress responses by helping plants protection from pathogens and pests. For example, during heat stress, certain miRNAs downregulate heat-sensitive genes and activate protective pathways. Similarly, during drought, miRNAs can help close stomata to reduce water loss or promote root growth for better water absorption. Because of their regulatory nature, miRNAs can be engineered or modulated to enhance desirable traits in crops, making them key players in the development of climate-smart agriculture.

Table 1. Role of miRNAs in Plant Stress Responses

miRNA	Crop	Role	Reference
miR169/NF-YA5	*Arabidopsis, rice, soybean*	Repressed under drought, allowing NF-YA5 (a drought-tolerance transcription factor) to accumulate	Li et al., 2008; Xu et al., 2014
miR398/CSD (superoxide dismutase)	*Arabidopsis, wheat*	Suppressed under drought/heat, salt stress, boosting antioxidant enzymes that neutralize stress-induced free radicals	Islam et al., 2022

miRNA	Crop	Role	Reference
miR430	*Wheat (Triticum aestivum)*	Heat-responsive miRNA that targets heat-shock protein genes; expression differs between heat-tolerant and heat-sensitive wheat cultivars, making it a candidate for breeding heat-tolerant wheat	Kumar et al., 2017
miR395	*General crops*	Regulates sulfate uptake and metabolism under nutrient (sulfur) deficiency	Kawashima et al., 2009
miR2118	*Rice*	Negatively regulates resistance to bacterial blight (*Xanthomonas oryzae*) by targeting NLR resistance genes	Zhu et al., 2023
miR394/LCR	*Tomato/ Arabidopsis*	Negative regulator of resistance to gray mold (*Botrytis cinerea*)	Tian et al., 2018

Major Advances in miRNA Research

The past decade has witnessed an explosion in miRNA research, made possible by high-throughput sequencing technologies. These tools have enabled the discovery of both conserved miRNAs (shared across species) and novel, species-specific miRNAs involved in stress responses. In crops like wheat, rice, maize, and soybean, researchers have identified numerous miRNAs linked to important traits such as heat and drought tolerance, disease resistance, flowering time regulation and nutrient efficiency. Recent advances in omics technologies genomics, transcriptomics, proteomics, and metabolomics are helping scientists uncover miRNA interactions. The integration of these datasets provides a comprehensive picture of how miRNAs function and how they can be harnessed for agricultural innovations. By correlating miRNA expression with specific traits, scientists are now able to manipulate gene expression more precisely than ever before.

Innovative Strategies Using miRNAs in Agriculture

As our understanding of miRNAs deepens, several cutting-edge strategies have emerged to harness their potential for crop improvement. Here are some of the most promising approaches:

1. Artificial miRNA (amiRNA) Technology

AmiRNAs are synthetic miRNAs engineered to target specific mRNAs with high precision. Designed to mimic the structure of natural miRNAs, they silence genes more effectively than traditional RNA interference (RNAi) methods, with fewer off-target effects.

In plants, amiRNAs have been used to inhibit viral replication, suppress genes involved in susceptibility to pathogens, Silencing undesirable traits. This approach allows for the customized regulation of genes, making it a powerful tool for developing resistant and high-performing crop varieties.

2. Short Tandem Target Mimic (STTM) Strategy

STTM is a molecular decoy technique. It uses short RNA fragments that mimic natural miRNA binding sites to silence up miRNAs, preventing them from interacting with their actual mRNA targets. This enables scientists to study gene function and even temporarily release gene suppression. STTMs are

particularly useful in functional genomics and trait discovery, allowing researchers to modulate gene activity without permanently altering the genome.

3. Topical application of pri-miRNAs or mature miRNAs

In a world of increasing genetically modified organisms (GMOs), transgene-free approaches are gaining more attention. One such method involves the topical delivery of miRNAs directly onto plant surfaces. Pri-miRNAs (precursor miRNAs) have better stability and are more easily absorbed by plant tissues compared to mature miRNAs. This technique enables temporary gene regulation without altering the plant's DNA, offering a safe and environmentally friendly solution for enhancing stress resistance.

4. CRISPR-Cas9 for miRNA editing

CRISPR-Cas9 is the game-changing genome-editing technology that allows for precise changes in DNA. When used to target miRNA genes or their binding sites, CRISPR can disrupt undesirable miRNA activity. The expression of stress-resistance genes will be enhanced, improving nutrient metabolism and disease resistance. By combining CRISPR with miRNA knowledge, scientists are paving the way for precisely edited, robust crops that can succeed in adverse environments.

Challenges and Opportunities

Functional validation: Many predicted miRNA-target interactions remain unverified.

Delivery systems: Efficient and scalable delivery methods for topical miRNA applications are still being optimized.

Regulatory frameworks: As miRNA-based technologies evolve, policies and public acceptance will shape their adoption. That said, the opportunities far outweigh the obstacles.

Future developments

miRNA-based diagnostics for plant stress detection

Synergistic approaches combining miRNAs, lncRNAs, and genome-editing tools. With continued collaboration between molecular biologists, agronomists, and data scientists, the next decade could see a model shift in how we breed crops.

Conclusion

Tiny though they are, miRNAs are proving to be giant players in the mission for sustainable agriculture. Their ability to regulate genes with extraordinary precision makes them ideal candidates for building crops that can survive and thrive under climate stress. Whether through artificial engineering, topical delivery, or genome editing, miRNAs are taking center stage in the agricultural innovation area. As we face an uncertain climate future, these small molecules could be the big solution we've been waiting for.

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PRECISION LIVESTOCK MANAGEMENT FOR SMART CALF REARING

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Abstract
Precision livestock management (PLM) involves the use of digital, sensor-based and automated technologies to collect and interpret individual-animal information and support management decisions. In calf rearing, such monitoring can complement routine observation by providing frequent information on feeding behaviour, activity, body temperature and growth. Research in calves has examined automatic milk feeders, accelerometers, infrared thermography, microphones and three-dimensional cameras, with different technologies operating at different stages of development from measurement to health-related decision support. These tools can identify deviations in normal behaviour and may provide early warning of health problems, but sensor alerts are not a substitute for clinical examination. This article outlines applications of PLM in calf health, feeding, growth monitoring and individual records, while considering validation, cost, data quality and evidence under Indian farm conditions.

Keywords: Precision livestock management; calf rearing; sensors; health monitoring; dairy calves

Introduction

Calf management depends on timely recognition of changes in feeding, activity, growth and health. Routine visual observation remains central to calf care, but observations made at fixed times can miss changes between checks. Precision livestock management (PLM) offers a complementary approach by collecting animal-level information through sensors, automated feeders, cameras and electronic identification systems. The purpose is not simply to add technology to the farm, but to convert measurements into information that can support a practical management decision.

Calves are an important population for precision monitoring because neonatal diarrhoea and bovine respiratory disease can occur during a period of rapid behavioural and physiological change. A systematic review identified automatic feeding stations, accelerometers, infrared thermography cameras, microphones and three-dimensional cameras among technologies investigated for automated calf-health monitoring. The review also described a progression from sensor technique and data interpretation towards information integration and decision support (Sun *et al.,* 2021). The literature commonly uses the term precision livestock farming (PLF) (Berckmans, 2017; Sun *et al.,* 2021); this article uses PLM to emphasize application to day-to-day calf-rearing decisions.

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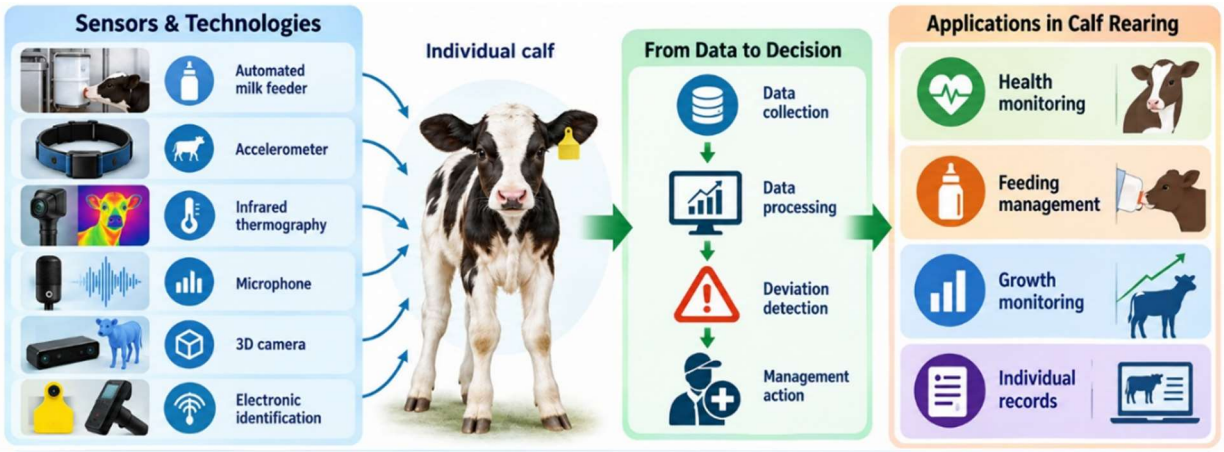


Figure 1. Precision Livestock Management Workflow for Smart Calf Rearing

1. Precision Livestock Management in Calf Rearing

PLM can be viewed as a sequence: an animal generates a measurable signal; a sensor or digital system records it; data are processed; a deviation or pattern is identified; and the information is considered by the farmer or veterinarian. The useful endpoint is a management decision rather than the measurement itself. A sensor alert may indicate that a calf requires closer observation without establishing the cause of the abnormality (Berckmans, 2017; Sun *et al.,* 2021).

2. Precision Health Monitoring

Accelerometers can measure activity and lying or standing patterns. Automated feeding stations can record milk intake, feeding visits and drinking behaviour. Temperature sensors and infrared thermography provide temperature-related information, while cameras and microphones can capture visual or acoustic indicators. Changes in feeding behaviour, activity, lying behaviour or temperature have been investigated as indicators of calf health (Sun *et al.,* 2021; Silva *et al.,* 2023).

For diarrhoea and respiratory disease, changes in feeding, activity, lying behaviour and temperature have been examined as potential early indicators. Some studies report changes before or around the time clinical abnormalities are detected, but performance varies with the technology, disease definition and validation method. Integrated systems combining accelerometers, temperature measurements and automated feeding data have also been investigated (Sun *et al.,* 2021). PLM should therefore be treated as a screening and early-warning aid. A detected deviation should prompt closer observation and, where indicated, clinical examination; it should not be treated as a diagnosis. Behavioural changes may also result from environmental stress, social effects or equipment problems.

3. Precision Feeding and Growth Monitoring

Colostrum management is the first step in nutrition of newborn calves, with emphasis on timely feeding of adequate quantities of good-quality colostrum to support adequate passive transfer of immunity. As the calf progresses to milk feeding, automated milk-feeding systems are among the more established precision applications in calf rearing. They can record individual milk intake, feeding visits and drinking behaviour and can help identify changes in a calf's feeding pattern. Automated feeders have also been used to manage gradual weaning according to solid-feed intake (de Passillé and Rushen, 2016). A reduction in milk intake may be associated with illness, but equipment malfunction or other management factors can produce a similar signal; investigation is therefore required before treatment.

Higher milk allowances can support greater pre-weaning growth under appropriate management conditions, as reported in experimental research and reviewed evidence (Jasper and Weary, 2002; Khan *et al.,* 2011). These studies do not establish that automated feeding itself produces a universal economic benefit. The value of automation depends on feeding strategy, labour requirements, farm scale and management conditions.

Regular growth measurement helps identify calves that are not developing as expected. Automated weighing platforms can provide more frequent individual measurements than periodic manual weighing. Recent work has examined non-contact body-weight estimation using a low-cost three-dimensional camera, indicating potential for repeated growth monitoring without physical restraint (Torrente *et al.,* 2026). Such measurements are useful when linked to an appropriate response, such as reviewing milk intake, starter consumption, health status or housing. Computer-vision-based weight estimation remains a developing application requiring validation under different farm conditions.

4. Computer Vision and Individual Calf Records

Computer vision uses cameras and image-processing or machine-learning methods to extract information from images or video. Calf research has examined body-size estimation, posture and activity recognition and other behavioural measurements; three-dimensional cameras have also been investigated for body-size and weight estimation (Silva *et al.,* 2023; Torrente *et al.,* 2026). Camera-based systems can obtain measurements without attaching a device to each calf, but lighting, occlusion, camera position, calibration and changing farm conditions can affect performance. Computer vision should therefore be considered a developing PLM tool rather than a universally validated diagnostic system.

Reliable individual identification is essential for linking sensor observations with a specific calf and connecting feeding, growth, health, vaccination and treatment records. Without reliable identification, measurements cannot be assigned confidently to individual animals. Electronic identification therefore provides the link between an animal and the information generated about it (Halachmi *et al.,* 2019).

5. From Data to Management Decision

A practical PLM workflow is: measure → analyse → detect deviation → alert → human assessment → management action. Data collection alone does not constitute precision management; the information must be interpretable and actionable. False or missed alerts can affect usefulness, while sensor placement, calibration, data quality, connectivity and maintenance influence reliability (Lee *et al.,* 2026).

Cost, maintenance, technical skills and data quality can limit adoption. Calf-specific reviews show that many technologies remain at the measurement or data-interpretation stage rather than providing fully validated farm-level decision support (Sun *et al.,* 2021; Silva *et al.,* 2023). Technologies developed in intensive housed systems may perform differently under Indian conditions because climate, housing, breeds, infrastructure and labour availability vary. Local validation is therefore needed before broad recommendations for commercial adoption.

6. Scope for Indian Dairy Farms

The feasibility of PLM technologies in India will depend on farm scale, infrastructure, labour availability, system cost and the management problem being addressed. On smaller farms, simpler

systems combining individual identification with basic health and growth records may be practical where they address a clearly defined need. Technology should be selected according to the management problem it is intended to solve. A simple system that reliably identifies reduced feed intake may be more useful than a complex system that generates data without a clear management response. Wider adoption should follow evidence of measurement reliability, usefulness, cost and suitability to Indian farm conditions.

Table 1. Examples of Precision Technologies and Their Potential Application in Calf Management

Technology	Information obtained	Management use
Accelerometer	Activity; lying and standing patterns	Identify changes requiring closer observation
Automated milk feeder	Milk intake; feeding visits; drinking behaviour	Identify changes in individual feeding pattern
Automated weighing system	Repeated body-weight measurements	Monitor individual growth trajectory
RFID/electronic identification	Individual animal identity	Link feeding, health and growth records
3-D camera/computer vision	Body size; posture; activity	Estimate body size/weight or monitor behaviour when validated
Temperature/thermal sensing	Body-surface or body-temperature information	Support health screening when validated

Conclusion

Precision livestock management can complement conventional calf care by providing more frequent individual-level information on feeding, activity, temperature and growth. Current calf research supports automated feeding systems, accelerometers, thermal sensing, cameras and related technologies for monitoring selected variables, but the maturity of these applications differs. Practical value depends on reliable measurements, appropriate interpretation and a clear management response. Sensor alerts should complement, rather than replace, observation and veterinary examination. Further validation under Indian production conditions is needed to identify technologies that are reliable, affordable and useful across different dairy-farm settings.

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PROBIOTICS AS AN ALTERNATIVE APPROACH TO DISEASE MANAGEMENT IN AQUACULTURE

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Abstract
Infectious disease is the largest single constraint on aquaculture productivity, and long reliance on antimicrobials has produced resistance concerns and tighter regulation. Probiotics reverse the logic of control: instead of killing pathogens once an outbreak begins, they shift the microbial balance in the gut and culture water so outbreaks are less likely to start. This article reviews the mechanisms, the microbial groups in use, and trial evidence in Nile tilapia and Pacific white shrimp, where better survival under challenge, stronger innate immunity and improved water quality are reported. Because benefits are strain-specific and dose-dependent, probiotics belong within integrated health management rather than serving as a direct antibiotic substitute.

Keywords: probiotics; aquaculture; disease management; antimicrobial resistance; *Bacillus*; fish health

Introduction

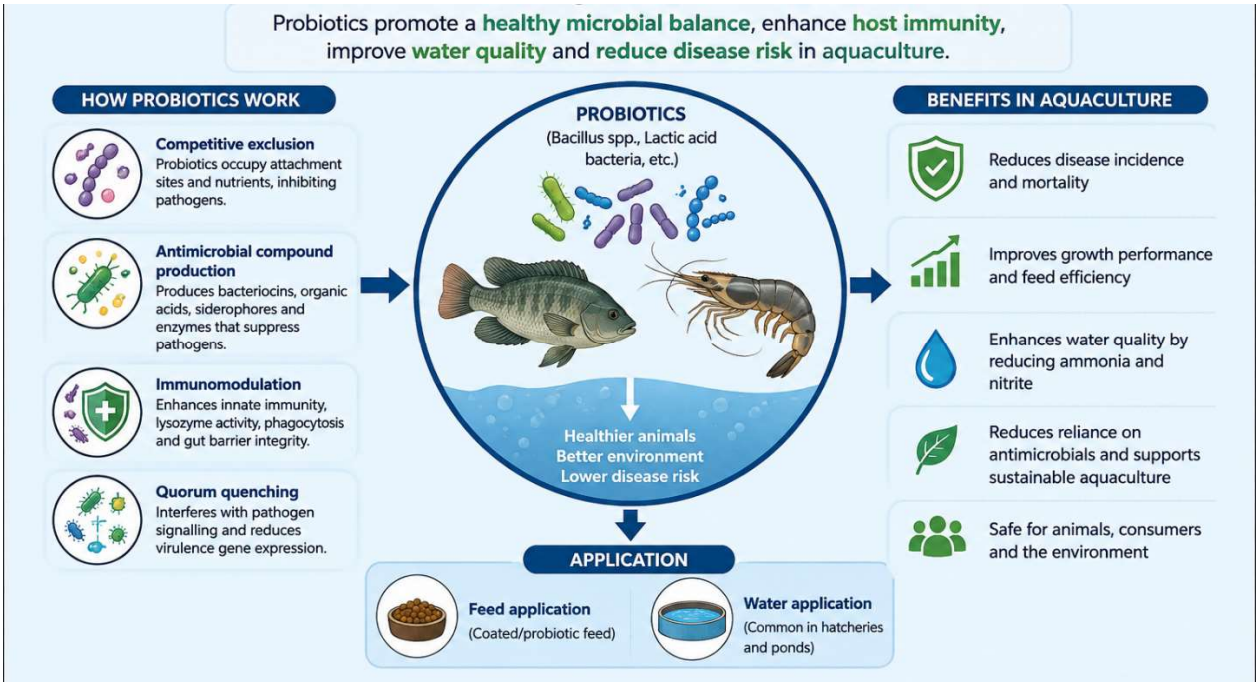
World aquaculture produced 130.9 million tonnes in 2022, including 94.4 million tonnes of aquatic animals — about 51 per cent of aquatic animal production and the first time farming exceeded capture fisheries (FAO, 2024). Intensification concentrates animals at densities they cannot escape, and disease has followed, costing roughly US$6 billion annually (Stentiford *et al*., 2017). Chemotherapy, the conventional answer, brought resistant bacteria, tissue residues, disturbed pond microbiota, and consumer concern, and Regulation (EU) 2019/6 now prohibits routine prophylactic antimicrobial use in farmed animals, including aquatic species.

Probiotics are live microorganisms which, in adequate amounts, confer a health benefit on the host (FAO/WHO, 2001). In aquaculture, the definition was broadened to include microbial additions that help the animal indirectly by modifying the water and its microbiota (Verschuere *et al*., 2000) — a necessary extension, since an aquatic animal and its environment share one microbial pool.

Mechanisms of Action

Several pathways operate at once. Competitive exclusion is the most direct: introduced strains occupy mucosal attachment sites and consume nutrients, while many secrete bacteriocins, organic acids and siderophores that suppress competitors (Verschuere *et al*., 2000). Immunomodulation is the second, with supplementation linked to elevated lysozyme and complement activity, stronger phagocytosis and better gut barrier integrity (Fachri *et al*., 2024); because teleost adaptive immunity is slow, non-specific enhancement matters most in juveniles and under stress. A third pathway interferes with pathogen signalling: Shaheer *et al*. (2021) characterised quorum-quenching *Bacillus* isolates that degrade N-acyl homoserine lactones and reduce virulence gene expression in *Vibrio harveyi*.

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Candidate Strains and Delivery

Bacillus species and lactic acid bacteria dominate both literature and market. Bacillus is practical: spores survive pelleting and storage, tolerate gastric passage, and secrete a broad range of enzymes. Delivery is usually through coated feed, with water application common in hatcheries and shrimp ponds. Effective doses generally fall between 10^6 and 10^9 colony-forming units per gram of feed, and the response is not monotonic, as excessive inclusion can depress performance (Fachri *et al*., 2024).

Evidence in Finfish and Shrimp

Nile tilapia illustrates both promise and variability. Panase *et al*., (2023) fed juveniles *Bacillus subtilis* with fructooligosaccharide and reported improved growth, stronger immune responses and greater resistance to *Streptococcus agalactiae*, with the synbiotic outperforming either component alone. Liao *et al*., (2023) found that *B. subtilis* DSM 32315 improved growth and immunity and raised tolerance of acute ammonia stress, with effects modulated by dietary protein level, so efficacy depends on nutritional context.

In shrimp, probiotics address diseases antibiotics handle poorly. Proespraiwong *et al*., (2023) identified *Bacillus* strains that reduced mortality from acute hepatopancreatic necrosis disease in *Litopenaeus vannamei*. Against white spot syndrome virus, where no antimicrobial applies, Dekham *et al*., (2023) showed protective anti-viral activity of *Lactobacillus johnsonii* KD1 in post-larvae, indicating that protection works largely through host defence. Water-applied products extend the logic to the pond, limiting ammonia and nitrite build-up; as ammonia is immunosuppressive, water quality and disease prevention are inseparable.

Limitations

Effects are strain-specific and rarely transferable across host species or temperature regimes. Much evidence comes from short tank trials with high challenge doses and little validation over full production cycles, and product quality is uneven.

Conclusion

Probiotics are a credible component of aquaculture disease management rather than a replacement for it. Trials in tilapia and penaeid shrimp show better survival under challenge, measurable immune gains and useful water-quality effects without residue or resistance liabilities. Their role is preventive and integrative, alongside sound nutrition, biosecurity, selective breeding and vaccination. Progress depends less on new bacteria than on rigorous strain characterisation, standardised trials and quality assurance.

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CONSERVING INDIGENOUS RICE LANDRACES OF MANIPUR: WHY THEY MATTER AND SIMPLE STEPS TO SAVE THE LIVING HERITAGE

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Abstract
Manipur (state in North-Eastern India) harbours a rich diversity of indigenous rice (*Oryza sativa* L.) landraces. There are more than 300 germplasms recorded. Among these the Chakhao landraces stand out as a genetic and cultural treasure. They valued for their aroma, colour, nutritional richness and deep-rooted place in Meitei traditions. These landraces offer superior nutritional benefits especially the black pigmented varieties. They also contain important genes for disease resistance and for local challenges like flooding and drought. These traditional varieties are very valuable, but they are disappearing because farmers are moving towards modern high-yielding crops. Conserving these landraces is essential for maintaining their genetic and cultural value. Seed preservation, farmer participation and scientific documentation can support their long-term conservation. GI tagging and market opportunities can further strengthen food security and protect their heritage for future generations.

Keyword- Rice landraces, Chakhao, North-Eastern India, Nutrition

Introduction

Rice (*Oryza sativa* L.) belongs to the genus *Oryza* under the family Poaceae. It serves as the staple food for billions of people across the globe. Worldwide, more than 110,000 rice varieties have been documented. India has long been recognized as a major centre of rice diversity. Historical records suggest that the country once cultivated over 200,000 rice varieties, though other estimates place the figure closer to 30,000. North-Eastern region of India holds a vast reserve of rice germplasm. Manipur, a state in North-Eastern India. It spans an area of 22,327 sq. km lying between 93°03'E to 94°78'E longitude and 23°83'N to 25°68'N latitude. The state comprises two distinct topographical



Figure 1. Seed of rice landraces

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zones: a central valley and the surrounding hill ranges. Rice is deeply woven into the life of manipuri people. The state is often referred to as the "rice bowl" of the region. Manipur is home to more than 300 rice landraces. These landraces differ widely in colour physicochemical composition, sensory attributes, nutritional value, bioactive properties and cooking and eating qualities. However, this rich diversity has been declining sharply in recent years. This article explains the importance landraces of Manipur. It also describes simple ways to conserve them.

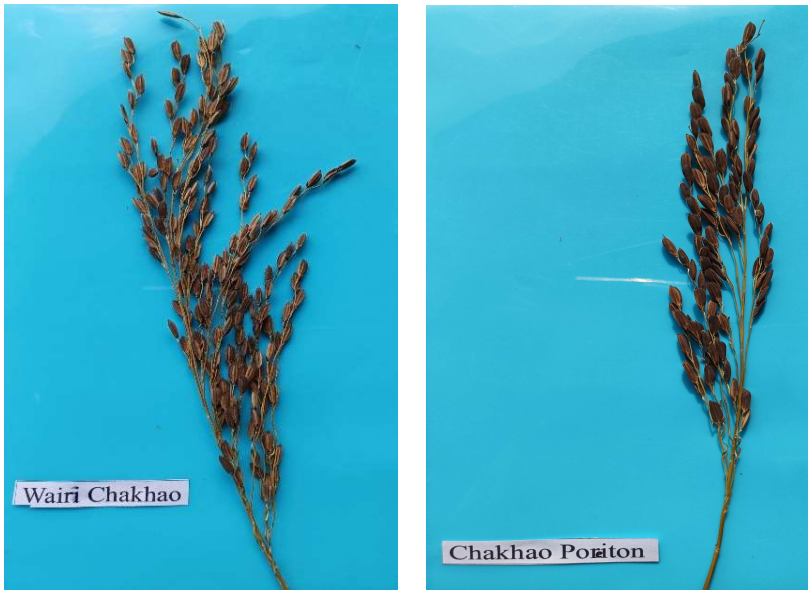


Figure 2. Panicle of rice landraces

Table 1. Well-known Landraces of Manipur

Sl. No.	Landrace	Grain Type	Special Trait / Use
1	Chakhao Amubi	Black, aromatic	Most popular black scented rice; rich in anthocyanins and antioxidants; used in festivals and desserts
2	Chakhao Poireiton	Black, aromatic	Along with Amubi, the most sought-after black rice; prized for colour and nutty aroma
3	Wairi Chakhao	Black/purple, aromatic	Traditional pigmented scented landrace grown across Manipur
4	Khurkhul Chakhao	Black/purple, aromatic	Traditional pigmented scented landrace
5	Pong Chakhao	Black/purple, aromatic	Traditional pigmented scented landrace
6	Chakhao Sempak	Black, aromatic	Popular black rice landrace, notable among Chakhao types
7	Chakhao Anganba	Red, aromatic	Red-scented rice cultivar
8	Langphou Chakhao	Red, aromatic	Red-scented rice cultivar

Sl. No.	Landrace	Grain Type	Special Trait / Use
9	Chakhao Angouba	White, aromatic	White-scented type; also grown as a non-pigmented aromatic upland variety
10	Taothabi	Non-pigmented	Flood-tolerant; thrives in deep-water conditions

What Are Rice Landraces?

Indigenous rice landraces are traditional rice varieties. They are gradually shaped over generations through the knowledge and selection practices of local farmers rather than being developed in a laboratory. he traditional rice landraces of Manipur are widely recognized under the collective name "Chakhao." The term "Chakhao" literally means "delicious rice," where *chak* refers to rice and *hao* means delicious. These traditional rice grains occur in a range of colours such as dark purple, red and white. The dark-coloured variants being popularly known as Manipur black rice.

The Rice Treasure of Manipur

The Chakhao landraces stand out as the true jewels of this collection. The well-known Chakhao varieties include Poireiton, Amubi, Sempak, Angouba and Ching Chakhao. Most farmers cultivate these on small plots, typically covering less than 10% of their total landholding. Historically, black rice held a special status. Historically associated with royalty, it was traditionally consumed by the Meitei community primarily during religious festivals and other significant occasions. Even today, it is prominently in community feasts and rituals. In Andro village black rice is used to prepare several traditional dishes such as kheer, thaotan, tanphut, and kabok matum. Some well-known feature of Manipur landraces are presented in the table 1 and in figure 1,2 with their significance.

Why We Conserve Them ?

1. Nutrition and Health

The dark pericarp is rich in anthocyanins, which are responsible for its characteristic deep colour and high antioxidant activity. Among Chakhao landraces, Chakhao Poireiton contains approximately 740 mg/kg of anthocyanins, while Chakhao Amubi contains about 692 mg/kg, compared with only around 134 mg/kg in ordinary white rice. Some Chakhao lines have reported that the anthocyanin levels exceeding 350–390 mg/100 g. Black rice is also characterized by a low amylose content ranging from 3.4% to 6.97%. The nutrient profiling of some varities are presented in the table 2.

Table 2. Nutritional Value of Black Rice and Its Traditional Preparations

Food Item	Key Finding
Poireiton Chakhao kheer	Highest antioxidant activity (51.21% DPPH); 13.49% protein; 5.08% fat; 55.56 mg GAE/100 g polyphenols
Kabok matum	Highest iron content (4.53 mg/100 g) and carbohydrate content (84.82%)
Tanphut	Highest zinc content (2.7 mg/100 g)
Chakhao Poireiton (grain)	740 mg/kg total monomeric anthocyanin
Chakhao Amubi (grain)	692 mg/kg total monomeric anthocyanin
White rice	134 mg/kg total monomeric anthocyanin

Threats to the local variety

The biggest threat to these landraces is replacement by modern cultivars. Which are gradually pushing local varieties towards extinction. Black rice is being a low-yielding crop often cultivated by

farmers only in small patches. While seed banks do preserve many landraces, farmers do not always have easy access to them.

Ways to Conserve Them

1. In Situ and Ex Situ Conservation - Both conservation strategies are essential. Ex situ conservation involves storing seeds in gene banks, while in situ conservation focuses on keeping landraces alive and thriving in farmers' fields. Tribal women have traditionally preserved and protected these valuable seeds.

2. Participatory Approaches - Farmers should be actively involved in seed selection and breeding processes. Participatory varietal selection allows farmers to trial and choose the best-performing local varieties themselves. while participatory plant breeding draws on farmer knowledge and input to improve landraces over time.

3. Scientific Characterization - Proper documentation of these varieties is essential. Farmers' traditional classification of chakhao closely matches modern genetic findings, which showing that indigenous knowledge is also scientifically valuable. Combining traditional knowledge with modern research methods can greatly strengthen conservation efforts.

4. Market-Linked Conservation - A fair and functioning market can help protect these landraces. Geographical Indication (GI) recognition can increase their value, while products such as black rice beer and cakes can create greater demand. When farmers receive good economic returns from growing these landraces, they are more likely to continue cultivating them.

Conclusion

Indigenous rice landraces of Manipur represent a precious living heritage. It is repository of nutrition, genetic wealth, history and hope. They shaped over generations through the patient efforts of local farmers. These landraces not only provide nutritional benefits but also hold significant cultural value. It represents the identity of the Meitei people. However, these valuable grains are slowly disappearing as farmers increasingly choose modern, high-yielding varieties. The loss of a landrace means the permanent loss of its unique genetic diversity and the cultural heritage associated with it. Thus, conserving these landraces requires more than simply storing seeds in refrigerated facilities. They should also be maintained as living crops in farmers' fields. This will help protect both food security and cultural heritage for future generations.

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RESTORING FISH HABITATS: FROM ARTIFICIAL REEFS TO RIVER RESTORATION

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Abstract
Fish habitats provide essential areas for feeding, breeding, spawning, shelter, and growth, but many aquatic ecosystems have been degraded by pollution, overfishing, dams, river modification, coastal development, and habitat destruction. Habitat restoration has therefore become an important component of fisheries conservation and management. Restoration approaches range from constructing artificial reefs and improving spawning grounds to reconnecting rivers with floodplains, restoring aquatic vegetation, and improving fish passage. Artificial reefs can provide additional physical structure and habitat for aquatic organisms, while river restoration can improve habitat diversity, connectivity, and access to important life-history areas. However, restoration does not automatically result in increased fish populations; its success depends on appropriate site selection, ecological design, species requirements, environmental conditions, and long-term monitoring. This article discusses the importance of fish-habitat restoration, the role of artificial reefs, and approaches for restoring rivers and freshwater ecosystems to support sustainable fisheries and aquatic biodiversity.

Keywords: Artificial reefs, river restoration, aquatic biodiversity, fish conservation, ecosystem rehabilitation.

Introduction

Healthy habitats are fundamental to productive fisheries because fish depend on suitable environments throughout their life cycles. Spawning grounds, nursery areas, feeding habitats, refuge areas, aquatic vegetation, wetlands, river channels, floodplains, and coastal ecosystems all provide different ecological functions. However, human activities have altered many aquatic environments through pollution, dam construction, channel modification, sedimentation, water abstraction, coastal development, and changes in land use. The Food and Agriculture Organization (FAO) has emphasized that rehabilitation of degraded inland waters is important for maintaining fisheries, ecosystem services, and aquatic biodiversity (FAO, 2008). Fish-habitat restoration aims to improve or recover the physical and ecological conditions required by aquatic organisms. Depending on the ecosystem, restoration may involve improving in-stream habitat, reconnecting fragmented rivers, restoring wetlands and floodplains, improving fish passage, protecting aquatic vegetation, or creating additional habitat structures. Restoration is increasingly viewed not simply as creating more habitat, but as restoring ecological processes and connectivity that allow fish populations to complete their life cycles (Roni *et al.,* 2005). In marine environments, artificial reefs are one approach used to introduce structural complexity to areas where natural habitat has been degraded or is limited. In freshwater ecosystems, restoration may focus on improving river channels, removing barriers, restoring flow patterns, and reconnecting rivers with floodplains.

These approaches can complement fisheries management by improving the ecological foundations on which fish populations depend. However, restoration projects need clearly defined objectives and long-term monitoring to determine whether they actually achieve the desired ecological outcomes (FAO, 2008; Rogosch *et al*., 2024).

Artificial Reefs: Creating New Homes for Fish

Artificial reefs are structures deliberately placed underwater to create or enhance habitat. They may be constructed from materials such as concrete or specially designed reef modules and can provide surfaces and shelter for fish, invertebrates, algae, and other organisms. By increasing the complexity of otherwise relatively uniform seafloor areas, artificial reefs can create feeding, shelter, and aggregation sites for aquatic organisms. They have been used for purposes including habitat restoration, fish-stock enhancement, fisheries management, and recreation (Fabi *et al*., 2015). The effectiveness of an artificial reef depends strongly on its design, material, location, depth, size, and relationship to surrounding natural habitats. Research has shown that different reef designs can produce different fish communities and levels of fish abundance. For example, location can significantly influence fish abundance, while reef complexity can affect species richness and community composition (Lemoine *et al*., 2019). Artificial reefs should therefore not simply be treated as structures that automatically increase fish production. Their ecological objectives need to be clearly defined before construction and followed by appropriate monitoring. Another important consideration is that artificial reefs are not necessarily substitutes for healthy natural habitats. A reef may attract fish without increasing overall fish production if it simply concentrates existing fish from surrounding areas. Long-term monitoring is therefore important for distinguishing genuine habitat enhancement from temporary aggregation. Research has also highlighted that many artificial-reef studies have relatively short monitoring periods, making long-term assessment particularly important (Lemoine *et al.,* 2022).

River Restoration: Bringing Back Healthy Fish Habitats

Rivers are dynamic ecosystems in which water flow, sediment movement, vegetation, depth, temperature, and connectivity interact to create habitats for fish. Human modification can simplify river channels, restrict fish movement, remove spawning habitat, and disconnect rivers from floodplains and wetlands. River restoration can address these problems through measures such as restoring natural channel features, improving environmental flows, adding suitable habitat structures, restoring riparian vegetation, removing unnecessary barriers, and reconnecting rivers with floodplains (FAO, 2008). Connectivity is particularly important for many fish species because they may need to move between feeding, nursery, and spawning habitats. Dams, weirs, culverts, and other barriers can interrupt these movements. Fish passes, bypass channels, barrier removal, and other connectivity measures can help restore movement between fragmented habitats. Recent research synthesizing river-restoration studies found that projects improving longitudinal connectivity showed particularly strong positive responses in fish density and species richness compared with some other restoration approaches (Rogosch *et al*., 2024). River restoration should also consider the wider watershed rather than focusing only on a small section of a river. Water quality, sediment supply, flow regimes, riparian vegetation, floodplains, and upstream land use can all influence whether restoration succeeds. FAO guidance recommends that rehabilitation objectives, methods, local social and economic conditions, and stakeholder interests be considered during project planning, followed by monitoring and modification where necessary (FAO, 2008).

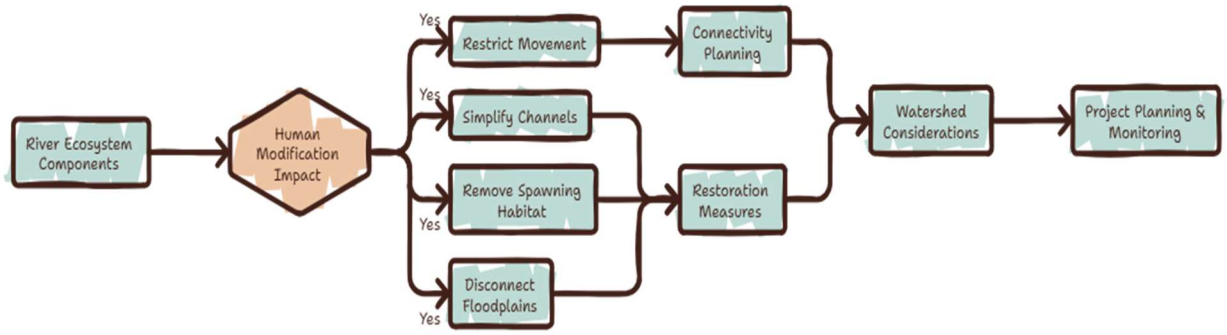


Figure 2 River Restoration Framework

From Restoration to Sustainable Fisheries: Why Monitoring Matters

Habitat restoration is ultimately intended to improve ecosystem function and, where appropriate, contribute to the recovery of fish populations. However, the presence of restored habitat does not necessarily mean that fish populations will immediately increase. Fish responses can vary according to species, habitat quality, connectivity, environmental conditions, recruitment, fishing pressure, and the size and location of the restoration project. A global review of river restoration studies found substantial variation in restoration outcomes and emphasized the importance of monitoring design, spatial and temporal scale, surrounding environmental conditions, and the ability of fish to recolonize restored areas (Rogosch *et al*., 2024). Monitoring should therefore be included from the beginning of a restoration project. Fish abundance, species richness, spawning activity, juvenile recruitment, habitat characteristics, water quality, and other indicators can be measured before and after restoration. Comparing restored sites with appropriate reference or control sites can provide stronger evidence of whether restoration has produced meaningful changes. FAO guidance similarly emphasizes that restoration projects should have clearly defined objectives and be monitored to determine whether those objectives have been achieved (Roni *et al*., 2005; FAO, 2008). Successful restoration also requires cooperation among fisheries managers, ecologists, local communities, engineers, government agencies, and fishers. Local communities may have valuable knowledge about historical fish habitats, seasonal changes, fishing grounds, and species distribution. Incorporating such knowledge alongside scientific monitoring can improve restoration planning and help ensure that restored ecosystems provide ecological as well as social benefits.

Conclusion

Restoring fish habitats is an important component of long-term fisheries conservation. Artificial reefs can introduce structural complexity and provide habitat in suitable locations, while river restoration can improve habitat quality, water connectivity, spawning opportunities, and access to nursery areas. However, restoration should not be viewed simply as constructing structures or modifying a river channel. Successful restoration requires understanding the ecological requirements of target species and restoring the processes that maintain healthy aquatic ecosystems.

The effectiveness of restoration also depends on careful site selection, appropriate design, protection from continuing threats, and long-term monitoring. Artificial reefs should complement rather than replace natural habitats, while river restoration should consider the entire watershed and the connectivity between different habitats. When restoration is combined with responsible

fishing practices, pollution control, habitat protection, and community participation, it can contribute to healthier aquatic ecosystems and more resilient fisheries.

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RIVERS, LAKES AND RESERVOIRS: UNLOCKING THE POTENTIAL OF INLAND FISHERIES

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Introduction

India possesses extensive and diverse inland fisheries resources, including rivers, canals, ponds, lakes, reservoirs, upland lakes, and floodplain wetlands. These water bodies have historically supported the livelihoods, income, and nutritional requirements of local communities. Indian inland waters also harbour highly diverse fish fauna, with approximately 1,035 fish species belonging to 326 genera. Fish and fisheries have long been associated with Indian culture and traditions and have contributed to food security and livelihood support, particularly in rural areas. Over the years, the fisheries sector has gained increasing importance in national development. India recorded a total fish production of approximately 197.75 lakh tonnes during 2024–25, of which inland fish production accounted for about 151.60 lakh tonnes. (Ministry of fisheries, 2026). The fisheries sector contributes to nutritional security, employment, income generation, and rural livelihoods and supports nearly 30 million fishers and fish farmers at the primary level. Inland fisheries are particularly important for rural and economically vulnerable communities, while associated activities such as fish processing, trade, and the manufacture of fishing crafts and gears provide additional livelihood opportunities.

Inland Fisheries Resources and Production

Inland Fish Production Systems

Inland fish production in India comprises capture fisheries in rivers, estuaries, lagoons, and lakes; aquaculture in ponds; and fisheries enhancement practices, particularly stocking and culture-based fisheries in reservoirs, lakes, and floodplain wetlands. Inland fish production has increased substantially in recent years, with inland production rising from 61.36 lakh tonnes in 2013–14 to 151.60 lakh tonnes in 2024–25. This growth has been associated mainly with the expansion of inland aquaculture and other fisheries development activities. Open-water capture fisheries have considerable scope for improvement, particularly in reservoirs and floodplain wetlands. These resources provide opportunities for stocking, culture-based fisheries, habitat improvement, and enhanced capture fisheries. In contrast, riverine fisheries are increasingly affected by habitat degradation and fishing pressure, which can limit further increases in production.

Contribution of Different Inland Water Resources

Inland fisheries production is derived from capture fisheries in rivers, estuaries, lagoons, and lakes, together with enhancement practices in reservoirs, floodplain wetlands, and other inland water bodies. The available resource-specific estimates indicate that approximately 55% of inland open-water capture fish production was associated with large reservoirs, small irrigation impoundments, and floodplain wetlands under enhanced fisheries, while rivers, lakes, estuaries, and lagoons together contributed approximately 45%. The earlier assessment estimated total inland capture fish production at approximately 2,144,452 tonnes. However, these resource-specific estimates were

based on assessments of fisheries that were not consistently monitored and therefore should be interpreted as assessment estimates rather than current annual national statistics. The latest national statistics show that inland fish production reached 151.60 lakh tonnes.

River Fisheries

Importance of River Fisheries

River fisheries have historically provided livelihood support, employment, and nutritional benefits to vulnerable communities across India. Indian rivers and their associated lakes and wetlands support considerable fish diversity, including approximately 906 freshwater and 138 brackishwater fish species. Riverine ecosystems therefore have importance not only for fisheries production but also for the conservation of aquatic biodiversity.

Important Fish Species in Riverine Fisheries

Riverine capture fisheries support several commercially and nutritionally important fish species. Major Indo-Gangetic carps include catla (*Labeo catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus mrigala*). Other commercially important carps include *Cirrhinus cirrhosus*, *Labeo fimbriatus*, *Labeo calbasu*, and *Labeo bata*, together with the peninsular carp *Hypselobarbus pulchellus*. Other important riverine fishes include featherbacks such as *Chitala chitala*; snakeheads such as *Channa punctata* and *Channa marulius*; and climbing perch (*Anabas testudineus*). Important catfishes include *Pangasius pangasius*, *Sperata aor*, *Sperata seenghala*, *Silonia silondia*, and *Hemibagrus punctatus*, along with smaller catfishes such as *Clarias magur* and *Heteropneustes fossilis*. Coldwater river fisheries support mahseer species such as *Tor putitora*, *Tor tor*, *Tor mussullah*, and *Tor khudree*, together with chocolate mahseer (*Neolissochilus hexagonolepis*) and snow trout species including *Schizothorax richardsonii* and *Schizothoraichthys* spp. Brackishwater-associated species include pearl spot (*Etroplus suratensis*) and mullets such as *Planiliza parsia* and *Mugil cephalus*. River fisheries also support freshwater prawns and shrimp, including *Macrobrachium rosenbergii*, *Macrobrachium malcolmsonii*, *Penaeus monodon*, and *Penaeus indicus*.

Fish Catch and Yield

Regular information on fish catches and yield rates from individual Indian rivers is not consistently recorded across states. Earlier observations from selected stretches of the Ganga, Brahmaputra, Narmada, Tapti, Godavari, and Krishna rivers reported yields ranging from approximately 5 to 3,300 kg/km. Because these estimates were obtained from short-duration surveys of selected river stretches, they should not be considered representative of the overall productivity of the respective river systems.

Challenges in River Fisheries

River fisheries are increasingly affected by habitat degradation, developmental activities, changes in river flow, and excessive exploitation of fish stocks. These pressures can reduce fish productivity and biodiversity. Sustainable river fisheries therefore require protection of aquatic habitats, restoration of degraded ecosystems, and improved management of fishing activities (Haque et al., 2026).

Floodplain Wetlands (Beels)

Distribution and Fisheries Importance

Floodplain wetlands are important inland fisheries resources, particularly in the eastern and northeastern regions of India. Earlier resource assessments estimated their extent at approximately 564,288 ha across seven states. Important floodplain wetland fisheries occur in Assam, West Bengal,

Uttar Pradesh, and Bihar, particularly in association with the Ganga, Brahmaputra, and Barak river systems. These wetlands provide livelihood opportunities for large numbers of fishers. Floodplain wetlands or beels are suitable for culture-based fisheries because of their nutrient-rich environment and abundance of natural fish food organisms. These conditions support rapid growth of stocked fish and can allow relatively high stocking densities. Their detritus-based food chains also provide opportunities for utilizing detritivorous fish species. In some wetlands, capture fisheries and culture-based fisheries are combined, while pen culture is also practiced.

Characteristics of Floodplain Wetlands

Floodplain wetlands are lentic water bodies located within river floodplains, particularly along flat and slow-flowing river stretches. They include oxbow lakes, sloughs, meander scroll depressions, residual channels, and backswamps. Depending on the region, these water bodies are known as beels, mauns, pats, and chaurs. They may occur as shallow depressions or abandoned river channels, with or without direct connections to the main river. During floods, connected wetlands may receive backflow from the parent river, while some wetlands also receive water from local catchments during the monsoon. These water bodies show considerable variation in morphology, ecological characteristics, and biological communities and support approximately 96 fish species.

Fish Diversity and Fisheries Practices

The fish composition of beels varies according to their connectivity with the parent river. Open beels generally support several riverine species in addition to resident fish species, whereas closed beels tend to possess more distinct fish communities. Riverine species may also enter closed beels through flooding or stocking. Common exotic carps include silver carp (*Hypophthalmichthys molitrix*) and common carp (*Cyprinus carpio*). Stocking of grass carp (*Ctenopharyngodon idella*) is generally discouraged in beels because the species may enter adjoining agricultural fields during the monsoon and damage young paddy plants.

Productivity and Ecosystem-Based Management

Floodplain wetlands are characterized by high organic productivity and considerable energy storage within detritus-based food chains. Their productivity can therefore respond positively to suitable stocking and management practices. Ecosystem-based management aims to utilize natural ecological processes, particularly water renewal patterns and the fish community of the associated river system. Both grazing and detritus-based food chains contribute to fish production. Important pathways include phytoplankton–zooplankton–fish and phytoplankton–zooplankton–minnows–catfish food chains. Detritus-based pathways include macrophytes–detritus–detritivores, phytoplankton–detritus–benthos–bottom feeders, and macrophytes–associated fauna–air-breathing fish.

Open beels are generally managed under capture fisheries, whereas closed beels are more suitable for culture-based fisheries. Wetland degradation, excessive weed growth, and restricted access for fishing remain important constraints to effective fisheries management.

Table 1. Fish production inland open water of India and their modes of management

Resources	Resource size	Catch (tonnes)	% of total inland open water fishery	Mode of management
Rivers (km)	164 118	392 609	18.31	Capture fisheries
Canals (km)	64 972	64 481	3.00	Capture fisheries

Resources	Resource size	Catch (tonnes)	% of total inland open water fishery	Mode of management
Estuaries (ha)	458 185	168 969	7.90	Capture fisheries
Lagoons (ha)	246 529	192 799	8.94	Capture fisheries
Reservoirs (ha)	3 460 301	446 311	20.81	Culture-based fisheries & Enhanced capture fisheries
Floodplain Wetlands (ha)	564 288	571 633	26.66	Culture-based fisheries, Enhanced capture fisheries
Lakes (ha)	35 688	33 890		Capture fisheries
Derelict water bodies	83 640	47 870	2.23	Capture fisheries
Other	64 091	225 890	10.53	Capture fisheries

Lakes and Upland Lakes

Distribution of Lakes

Major natural lakes are relatively limited in the plains of India, except for the taals of Uttar Pradesh and smaller water bodies occurring in states such as Andhra Pradesh, Kerala, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura. The taals of Uttar Pradesh are mainly detached portions of oxbow lakes that became separated from their parent rivers following changes in river courses. In contrast, numerous lakes occur in upland areas, although many are situated in remote and difficult-to-access locations. Earlier assessments estimated approximately 84,130 ha of lakes in Ladakh and 7,275 ha in Jammu and Kashmir, although many of these water bodies have not been comprehensively surveyed and documented.

Fisheries of Upland Lakes

Information on capture fisheries in upland lakes remains limited. Natural lakes in colder upland regions were estimated to cover approximately 91,561 ha. These water bodies support indigenous and exotic fish species, including schizothoracids, mahseers, trout, tench (*Tinca tinca*), crucian carp, and mirror carp (*Cyprinus carpio* var. *specularis*).

Fish Yield

Reported fish yields vary considerably among upland lakes and regions. In peninsular upland lakes, annual yields have been reported at 1.8–9.3 kg/ha in Kodaikanal, 16.7–49.5 kg/ha in Yercaud, and 33.0–111.0 kg/ha in Ooty. In Himalayan lakes, reported yields range from 8.0–22.5 kg/ha in Dal, 10.0–28.5 kg/ha in Anchar, 15–45.0 kg/ha in Wular, 2.0–6.0 kg/ha in Manasbal, and 5.0–15.0 kg/ha in Sivalik lakes (FAO,2024).

Estuarine Fisheries

Importance and Production

Estuarine systems constitute an important component of India's fisheries resources. Earlier assessments estimated their area at approximately 458,185 ha. Their fish catches are generally included within inland capture fisheries statistics, and the fisheries operate beyond subsistence levels. Average yields have been estimated at approximately 45–75 kg/ha. Several Indian estuaries have been investigated for their fisheries potential, although continuous monitoring has been more consistently undertaken in the Hooghly–Matlah estuarine system.

Major Constraints

Changes in river courses and modifications of estuarine environments can adversely affect fish populations and fisheries production. In the Mahanadi Estuary, sand-bar formation at the sea mouth has reduced tidal exchange and flood discharge, affecting fish yields. Similar effects have been reported in the Godavari Estuary. The fisheries potential of the Tapti Estuary declined following the commissioning of the Ukai Reservoir, while industrial activities along the Mahi River have contributed to pollution pressures in the estuary.

Lagoons and Backwaters

Lagoons and backwaters associated with estuarine systems are important fishery resources. Major brackish water lagoons on the eastern coast include Chilika Lagoon, covering approximately 87,000 ha, and Pulicat Lagoon, covering about 79,000 ha. (Patra et al., 2024). Kerala supports a chain of lagoons covering approximately 46,129 ha, including Vembanad Lagoon. These ecosystems support important fisheries and contribute to the production of fish and other aquatic organisms.

Bheries of Kolkata

Bheries are estuarine wetlands around Kolkata that contribute substantially to fish supply for the city and surrounding areas. Earlier assessments estimated that these wetlands covered approximately 40,000 ha and received treated and untreated municipal wastewater. However, urban expansion and increasing pressure on land have contributed to the decline of these fishery resources.

Mangrove Fisheries

Mangrove ecosystems are biologically sensitive habitats that provide important breeding and nursery grounds for commercially valuable riverine and marine organisms. Mangrove resources occur along the coasts of Kutch and Cambay in Gujarat, in patches along the Konkan and Malabar coasts, around the Andaman and Nicobar Islands, and in the estuaries of the Cauvery, Mahanadi, and Hooghly–Matlah systems. Earlier assessments reported that approximately 85% of Indian mangroves were concentrated in the Sundarbans of West Bengal and the Bay of Bengal islands. The Indian portion of the Sundarbans was reported to have declined from an earlier area of approximately 4,262 km² to about 3,560 km² (Mallick et al., 2023). Mangrove degradation has also affected the extent of mangrove-associated fisheries. Mangrove areas are generally protected, with fishing either prohibited or restricted to subsistence activities in many locations. Several mangrove creeks serve as important sites for fish and prawn seed collection. The Sundarbans fishery has been reported to include approximately 18 prawn species, 34 crab species, 120 fish species, and four turtle species. Mangrove fisheries are important to local communities; however, reliable production estimates remain limited because systematic fisheries statistics are not consistently collected.

Reservoir Fisheries

Importance and Fisheries Potential

Reservoirs are widely distributed across India and represent one of the major inland fisheries resources because of their large water spread and considerable potential for fisheries enhancement. Earlier resource assessments estimated approximately 3.46 million ha of reservoirs and a production of about 446,311 tonnes from reservoir fisheries. Reservoir fisheries have gained increasing importance because river ecosystems are affected by habitat degradation and marine capture fisheries face limitations to further expansion. The Government of India has also recently

emphasized the development of reservoir fisheries, including integrated development of selected reservoirs and Amrit Sarovars and the promotion of fisheries through community participation.

Reservoir Fisheries Enhancement

Reservoir production can be improved through suitable enhancement practices according to the ecological characteristics of individual water bodies. Culture-based fisheries are particularly appropriate for shallow and seasonal reservoirs with relatively small water spread areas. In deeper and larger reservoirs, enhanced capture fisheries can be adopted where stocked fish are able to establish breeding populations and support sustainable production. Recent government initiatives have also supported reservoir fisheries through cage and pen culture, stocking, and integrated reservoir development. Under PMMSY, more than 62,000 cage units, about 545 ha of pens, and stocking of fingerlings over more than 3 lakh ha have been supported, along with integrated development of selected reservoirs (Chand et al., 2025).

Community-Based Reservoir Fisheries Management

Effective community participation is important for sustainable reservoir fisheries. Cooperative societies, self-help groups, and other fisher organizations can participate in stocking, maintenance of fish stocks, harvesting, and marketing. Earlier observations from beel fisheries in Assam demonstrated improvements in fish yield under community-based management. Between 2001–02 and 2020–21, yields increased from 123 to 222 kg/ha/year in Son Beel, 287 to 303 kg/ha/year in Rowmari, 366 to 537 kg/ha/year in Lakhanabandha, and 311 to 1,011 kg/ha/year in Sibsthan–Potakollong.

Conclusion

India's rivers, lakes, reservoirs, floodplain wetlands, estuaries, lagoons, and upland lakes provide substantial potential for inland fisheries development and contribute to fish production, food security, employment, and rural livelihoods. Sustainable utilization of these resources requires resource-specific management, fisheries enhancement, habitat restoration, community participation, and improved monitoring. Balancing fisheries development with ecosystem conservation will be essential for increasing production while maintaining aquatic biodiversity and long-term sustainability.

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PLANT SECONDARY METABOLITES UNDER BIOTIC STRESS: ROLE IN PLANT DEFENSE AND HERBIVORE INTERACTIONS

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Abstract
Biotic stresses caused by pathogens and herbivores can significantly influence plant secondary metabolism. Secondary metabolites are diverse compounds that contribute to plant defense, adaptation, and survival under stress. Their production can increase following stress perception through the activation of defense-related signaling pathways. Major groups, including phenolics, flavonoids, terpenoids, alkaloids, glucosinolates, and other defense-associated compounds, contribute to plant protection. These metabolites may directly affect pathogens and herbivores or influence their behavior. Herbivory can also alter reactive oxygen species and antioxidant responses and stimulate the emission of volatile organic compounds. Biotic and chemical elicitors, as well as plant hormones such as salicylic acid and gibberellic acid, can further influence secondary-metabolite production. Thus, changes in secondary metabolism represent an important component of plant responses to biotic stress and herbivore attack. Understanding these changes is useful for studying plant defense mechanisms and plant–insect interactions.

Keywords: secondary metabolites, pathogens, insect, plant defense

Introduction

Increasing pressure from pathogens, insect pests, nematodes, and weeds poses a major challenge to sustainable crop production by reducing plant growth, productivity, and yield quality. This has created a growing need for environmentally safe and sustainable approaches to crop protection. Plants naturally respond to these biotic challenges through a complex defense system in which secondary metabolites (SMs) play a central role. Approximately 200,000 plant secondary metabolites have been identified and characterized, highlighting their remarkable chemical diversity (Satish *et al*., 2020).

Plant SMs are diverse compounds formed from primary metabolic pathways and are broadly grouped into terpenes, phenolics, nitrogen-containing compounds, and sulfur-containing compounds. Although these metabolites are not directly required for basic plant growth and development, they are crucial for plant defense, adaptation, and survival. When plants recognize attack by pathogens or herbivores, defense signaling pathways are activated and metabolic processes are redirected toward the synthesis and accumulation of protective compounds (Zandalinas *et al*., 2017).

As a result, compounds such as phenolics, flavonoids, terpenoids, alkaloids, and other antioxidant metabolites may accumulate in affected tissues. These metabolites can act directly by inhibiting pathogens, reducing herbivore feeding or development, and limiting tissue damage. They can also function indirectly by altering plant volatile emissions and attracting beneficial organisms such as predators and parasitoids. Thus, plant secondary metabolism represents a dynamic and highly

coordinated defense system that enables plants to respond to biotic stress while shaping their interactions with the surrounding environment.

Role of Secondary metabolites in biotic stress:

1. Terpenes

Terpenes are one of the largest and most diverse groups of plant secondary metabolites. They are synthesized through the mevalonate (MVA) and methylerythritol phosphate (MEP) pathways from five-carbon isoprene units. Terpenoids are structurally modified forms of terpenes and contribute to plant growth, signaling, defense, and interactions with herbivores and microorganisms. Based on their carbon skeletons, they are classified as monoterpenes (C10), sesquiterpenes (C15), diterpenes (C20), sesterterpenes (C25), triterpenes (C30), tetraterpenes (C40), and polyterpenes. Monoterpenes and sesquiterpenes are particularly important in plant defense because of their volatility and biological activity. They can directly deter herbivores and inhibit pathogens or indirectly defend plants by attracting predators and parasitoids. Diterpenes and triterpenes also contribute to chemical defense through antimicrobial, antifungal, and insecticidal activities. Sesterterpenes, although less abundant, possess considerable structural diversity and biological potential, including antimicrobial and pharmacological activities. Polyterpenes primarily contribute to structural and protective functions.

Importantly, herbivore attack can alter terpene biosynthesis and induce the release of volatile terpenes. These herbivore-induced compounds can influence insect feeding, host selection, and interactions with natural enemies, making terpenes important components of plant chemical defense and plant–insect communication (Mahizan *et al*., 2019).

2. Phenolic Compounds

Phenolic compounds are one of the most abundant and diverse groups of plant secondary metabolites. They are primarily synthesized through the shikimate and phenylpropanoid pathways and are characterized by one or more aromatic rings bearing hydroxyl groups. Phenolics contribute to plant pigmentation, UV protection, antioxidant activity, and defense against herbivores and microbial pathogens (Santos-Sánchez *et al*., 2019).

Important phenolic groups include flavonoids, coumarins, lignin, isoflavones, and tannins, each contributing to plant defense through distinct mechanisms. Flavonoids, including flavonols, flavones, flavanones, flavan-3-ols, and isoflavones, possess antioxidant and antimicrobial properties and can contribute to resistance against pathogens and herbivores. Coumarins, synthesized mainly through phenylpropanoid metabolism, participate in plant defense and can inhibit microbial growth. Lignin, a complex phenolic polymer, strengthens cell walls and forms a physical barrier against pathogen invasion. Isoflavones are particularly important in plant–microbe interactions and contribute to disease resistance. Tannins, owing to their ability to bind proteins and other cellular components, can reduce herbivore digestion and inhibit microbial activity.

These metabolites play a central role in plant defense and biotic stress tolerance by combining antioxidant, antimicrobial, structural, and anti-herbivore functions. Herbivore-induced changes in phenolic accumulation can therefore serve as important indicators of plant defense responses and are highly relevant to metabolomic studies of plant–insect interactions.

3. Nitrogen-Containing Compounds

Nitrogen is an essential element for plant growth and metabolism and serves as a precursor for several nitrogen-containing secondary metabolites. These compounds have diverse biological

functions and are particularly important in plant defense against herbivores and pathogens. Among them, alkaloids and cyanogenic glycosides are major classes associated with plant protection.

Alkaloids are structurally diverse nitrogen-containing compounds, generally characterized by nitrogen incorporated into heterocyclic structures. Major groups include tropane, indole, pyrrolidine, pyrrolizidine, purine, and isoquinoline alkaloids. Many alkaloids possess strong biological activities, including antimicrobial, toxic, and anti-herbivore effects, and therefore contribute to plant resistance against biotic stress. For example, alkaloid-rich extracts of *Datura stramonium* and *Peganum harmala* have demonstrated antimicrobial activity against several Gram-positive and Gram-negative bacteria.

Cyanogenic glycosides are nitrogen-containing plant metabolites composed of a sugar moiety linked to an α-hydroxynitrile group. They are synthesized from amino acids through a series of hydroxylation, oxime, nitrile, and glycosylation reactions. Following tissue damage, cyanogenic glycosides can release hydrogen cyanide, which acts as a potent chemical defense against herbivores and microorganisms. Thus, these compounds contribute significantly to plant protection and stress tolerance (Vetter, 2000).

Nitrogen-containing secondary metabolites are important components of plant chemical defense. Their accumulation and transformation during herbivore attack can influence insect feeding, survival, and pathogen development, making alkaloids and cyanogenic glycosides important targets in metabolomic studies of plant–insect interactions.

4. Sulfur-Containing Compounds

Sulfur-containing secondary metabolites form a relatively small but important group of plant defense compounds. They participate in redox regulation, antioxidant protection, detoxification, and defense against pathogens, thereby helping plants cope with biotic and oxidative stress (Venditti and Bianco, 2020).

Glutathione is a major sulfur-containing metabolite involved in maintaining cellular redox balance, antioxidant defense, detoxification, and normal plant development. Changes in glutathione metabolism are closely associated with plant responses to biotic stress.

Glucosinolates are sulfur-rich thioglucosides particularly abundant in Brassicaceae. Following tissue damage, their hydrolysis produces biologically active compounds that can deter herbivores and suppress microbial pathogens, making them important components of plant chemical defense.

Thionins are sulfur-containing antimicrobial peptides that contribute to plant resistance against fungi and other microorganisms. They can disrupt microbial membranes and participate in defense signaling and cell-wall-associated responses. Thus, sulfur-containing metabolites collectively contribute to antioxidant protection, antimicrobial activity, and herbivore defense, making them important components of plant responses to biotic stress.

Secondary Metabolites under Biotic Stress and Herbivory

Biotic stress caused by pathogens and herbivorous insects can profoundly influence plant secondary metabolism. When plants perceive an attack, they activate defense-signaling pathways that redirect metabolic resources toward the production of protective compounds. The resulting secondary metabolites can inhibit pathogens, discourage herbivore feeding, strengthen plant tissues, regulate oxidative stress, and mediate interactions with beneficial organisms. Therefore, changes in

secondary-metabolite profiles provide important insights into the mechanisms underlying plant resistance. The production of secondary metabolites can also be stimulated by biotic and chemical elicitors. Microbial components, including bacteria, fungi, yeast-derived preparations, chitin, and cell-wall fragments, can activate defense pathways and enhance the accumulation of compounds such as alkaloids, flavonoids, coumarins, and saponins. For example, rhizobacterial treatment has been reported to stimulate hypericin and pseudohypericin production in *Hypericum perforatum*, while fungal elicitation enhanced alkaloid accumulation in *Ruta graveolens*. Similarly, oligo-galacturonic acid can promote saponin production in *Panax ginseng*. Plant hormones also contribute to this metabolic regulation; salicylic acid and gibberellic acid can influence the synthesis of phenolics, flavonoids, tanshinones, alkaloids, and terpenoids, with salicylic acid functioning as an important regulator of plant defense responses (Hao *et al*., 2015).

Herbivory-induced changes in secondary metabolism

Herbivore feeding represents a particularly important trigger of secondary metabolic reprogramming. Following insect attack, plants can increase the synthesis of terpenoids, phenolics, alkaloids, glucosinolates, oxylipins, and other defense-associated metabolites. These compounds may directly reduce herbivore growth, feeding, and survival or indirectly enhance defense by attracting predators and parasitoids (Mithöfer and Boland, 2012).

Terpenoids, particularly monoterpenes and sesquiterpenes, are important components of herbivore-induced defense. Their accumulation or emission can deter insects and modify their host-selection behavior, while volatile terpenoids may serve as chemical signals that recruit natural enemies. Other plant-derived compounds, including pyrethrins and azadirachtin, possess strong insecticidal or antifeedant properties and further demonstrate the defensive potential of plant secondary metabolism.

Herbivory can also enhance phenolic and alkaloid metabolism. Alkaloids such as nicotine can interfere with insect nervous-system activity, whereas phenolic compounds may reduce herbivore performance through effects on digestion and cellular processes. Glucosinolates and their breakdown products provide another important chemical barrier, although specialist herbivores have evolved mechanisms to detoxify, tolerate, or sequester these compounds. This chemical interaction highlights the ongoing co-evolution between plants and their herbivores.

Insect feeding is additionally associated with changes in reactive oxygen species (ROS) and antioxidant metabolism. Herbivore-induced tissue damage can stimulate ROS production, which acts not only as a source of oxidative stress but also as an important defense signal. Antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase help regulate ROS levels, while lipoxygenase-mediated pathways contribute to the formation of oxylipins involved in defense signaling.

A further hallmark of herbivore attack is the release of volatile organic compounds (VOCs), including green-leaf volatiles, monoterpenes, sesquiterpenes, and homoterpenes. These compounds can alter insect feeding, oviposition, host-plant recognition, and mate-finding, while simultaneously attracting parasitoids and predators. Thus, herbivore-induced VOCs extend plant defense beyond the damaged tissue and facilitate communication with other organisms.

Overall, biotic stress and herbivory induce coordinated changes in plant secondary metabolism rather than affecting individual metabolites in isolation. The resulting metabolic adjustments

integrate direct chemical defense, antioxidant protection, signaling, and indirect recruitment of natural enemies. Consequently, metabolomic and multi-omics approaches provide powerful tools for characterizing these dynamic biochemical responses and for understanding the molecular basis of plant–insect interactions (Erb and Reymond, 2019).

Conclusion

Biotic stress triggers substantial changes in plant secondary metabolism, enabling plants to mount effective responses against pathogens and herbivores. The increased production of compounds such as phenolics, flavonoids, terpenoids, alkaloids, glucosinolates, oxylipins, and other defense-related metabolites contributes to plant protection through multiple mechanisms. Herbivore feeding can modify the chemical profile of affected tissues, stimulate antioxidant responses, and promote the release of volatile compounds that influence interactions with natural enemies. In parallel, herbivores may develop strategies to tolerate, detoxify, or utilize plant defensive chemicals, reflecting the complex relationship between plants and insects. Thus, secondary metabolites function as interconnected components of the plant defense system rather than as independent compounds. Combining metabolomics with transcriptomics, proteomics, and phytohormone profiling can help clarify these coordinated responses and improve our understanding of plant defense mechanisms.

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IMPORTANCE OF LIVE FEEDS IN AQUACULTURE

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Abstract

Live feed is a central component of hatchery production, particularly during the first-feeding and early larval stages of marine fish and crustaceans. Newly hatched larvae often possess small mouth, limited digestive capacity and high requirements for readily available nutrients. Rotifers, Artemia, copepods and microalgae can provide appropriately sized, motile prey and can function as carriers of essential fatty acids and other nutrients. Their value depends on species-specific prey size, culture quality, enrichment, hygiene and feeding management. This article outlines the biological importance of live feeds, the functions of major hatchery live-feed organisms, the role of enrichment and the principal management precautions required for reliable larval production. Live feeds should not be viewed as a universal replacement for formulated diets; rather, they form part of a staged feeding programme that should progressively incorporate weaning and species-specific nutritional validation.

Keywords: Microalgae, Rotifers, Artemia, Copepods, Larval nutrition

Introduction

Live feeds such as phytoplankton and zooplankton are widely used as initial food sources for many aquaculture species (Bengtson, 2007). They are the main item in the diet of cultured fish larvae and they are of particular importance when rearing marine fish larvae of the altricial type (Conceição et al., 2010). They contain a rich composition of macro- and micronutrients, which is why they are often referred to as “living capsules of nutrition”. Since these organisms remain freely suspended in the water and are continuously available, they serve as an ideal food source for newly hatched fish larvae. Furthermore, their active movement within the water column, characterised by jerky motions, stimulates the feeding response of larvae and enhances feed intake (Bengtson, 2007). A live feed is particularly essential for larval growth in aquaculture, as it is more easily ingested and digested, does not affect water quality, and contains essential growth factors such as fatty acids and amino acids (Radhakrishnan et al., 2019). Rotifers, copepods and brine shrimp (Artemia) nauplii are the most widely used live feed in aqua-hatcheries for the first exogenous feeding of marine finfish larvae (Radhakrishnan et al., 2019; Altaff, 2020).

Why live feed is important?

Live prey offers several functional advantages over many early formulated diets. Motility stimulates larval feeding responses and allows prey to remain suspended in the water column. The small size and variable size classes of rotifers, copepods and Artemia permit feeding programmes to be matched to larval mouth gape and developmental stage. Live organisms can also be nutritionally manipulated before feeding, allowing the hatchery to deliver selected fatty acids (FAs) and other nutrients through enrichment. These properties are particularly relevant in species whose larvae

have incomplete digestive development or demanding requirements for marine long-chain polyunsaturated fatty acids (PUFAs) (Conceição et al., 2010; Hamre et al., 2013).

Table 1. Major live feeds used in hatcheries

Sr. No.	Live feed	Principal hatchery role	Important management point
1	Microalgae	Direct food for some larvae or zooplankton feed; may also support green-water culture systems.	Control species, cell density, avoid contamination and nutritional consistency.
2	Rotifers	Common starter prey for small-mouthed larvae; available in different size classes.	Maintain culture hygiene and enrich when the target larvae require improved fatty-acid delivery.
3	Artemia nauplii	Widely used after the earliest feeding stage because nauplii are readily hatched and harvested.	Cyst quality, hatching conditions, harvest timing, washing and enrichment.
4	Copepods	Natural-type prey with strong relevance to marine larval nutrition and behaviour.	Mass culture can be technically demanding; use appropriate size and reliable production protocols.

Rotifers as first-feed organisms

Rotifers are widely used as starter prey because their size (100-300 µm) is suitable for many early marine fish larvae and because they can be cultured at high densities (100-200 number/ml). Their nutritional value is not fixed: it depends on strain, culture diet and enrichment procedure. Enrichment can improve their value as a carrier of nutrients for marine larvae, but the procedure should be matched to the requirements of the target species (Sorgeloos and Léger, 1992; Hamre et al., 2013).

Artemia

Artemia nauplii are valuable because cysts can be stored and hatched when required. Nevertheless, cyst origin, nauplius size, hatching quality and biochemical composition can vary. Freshly hatched nauplii may not provide sufficient levels of all nutrients required by marine larvae, particularly when the target species has high requirements for Docosahexaenoic Acid (DHA) and other long-chain fatty acids. Enrichment can improve the nutritional profile before Artemia is offered to larvae (Dhert et al., 1993; Hamre et al., 2013).

Copepods and nutritional realism

Copepods are important live prey in natural marine hatcheries and are increasingly considered valuable in hatchery feeding programmes. Their size range, movement and biochemical composition can be advantageous for larvae that perform poorly on conventional rotifer–Artemia schedules. However, copepod production is technically demanding and must be matched to the target fish, culture conditions and biosecurity requirements (Støttrup, 2003).

Enrichment and feed hygiene

Enrichment should be based on the nutritional requirements of the predator larvae, not applied as an indiscriminate routine. The procedure must consider enrichment product, exposure duration, prey density, oxygenation, temperature and washing before feeding. Live feeds can also carry

suspended solids and microorganisms into larval tanks. Therefore, hatchery protocols should include clean culture vessels, controlled water exchange, appropriate sanitation, careful harvesting and rinsing, and regular monitoring of culture performance (Sorgeloos and Léger, 1992; Dhert et al., 1993).

Feeding strategy and transition to formulated diets

A successful hatchery feeding programme is staged. Larvae should receive prey that matches their gape and swimming ability, and feeding frequency should maintain adequate prey availability without excessive accumulation. As larvae develop functional digestive organs and improved capture ability, enriched live feeds can be combined with microdiets. Weaning should be gradual and evaluated using survival, growth, deformity incidence, stress tolerance and post-larval quality (Conceição et al., 2010; Hamre et al., 2013).

Conclusion

Live feeds remain fundamental to hatchery production because they combine appropriate prey size, movement, digestibility and nutritional flexibility during vulnerable larval stages. Rotifers, Artemia, copepods and microalgae each occupy different roles, and their value depends on culture quality and management. Enrichment can correct important nutritional limitations, but it must be linked to larval requirements and supported by strict hygiene. The most reliable approach is a staged, species-specific feeding programme that integrates live prey with formulated diets as larvae develop.

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SINGLE-CELL RNA SEQUENCING: A NEW ERA OF HIGH-RESOLUTION PLANT TRANSCRIPTOMICS

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Abstract

Traditional transcriptomic studies have largely relied on bulk tissue samples, in which gene expression is averaged across thousands of cells. Although these approaches have provided valuable insights into plant biology, they often mask the cellular heterogeneity and distinct molecular responses of individual cell types. Single-cell RNA sequencing (scRNA-seq) has emerged as a transformative approach that enables high-resolution analysis of gene expression at the level of individual plant cells. By capturing cell-to-cell variation, scRNA-seq facilitates the identification of diverse cell types, developmental states, and cell-specific transcriptional programmes within complex plant tissues. Recent advances in single-cell isolation, RNA capture, amplification, sequencing, and computational analysis have further improved the resolution and reliability of plant transcriptomic studies. This technology has enhanced our understanding of fundamental processes such as plant growth, differentiation, tissue organisation, and responses to biotic and abiotic stresses. Integration of scRNA-seq with other single-cell and spatial multi-omics approaches is also providing a more comprehensive view of plant cellular functions and interactions. Beyond basic research, high-resolution plant transcriptomics holds considerable potential for crop improvement by identifying genes and cellular pathways associated with stress tolerance, productivity, and desirable agronomic traits. Thus, scRNA-seq represents an important step toward precision plant biology, sustainable agriculture, and the development of climate-resilient crops.

Keywords: Single-cell RNA sequencing, Transcriptomics, metabolomics, differentiation

Introduction

Agriculture faces major challenges such as climate change, soil degradation, biotic and abiotic stress, and the need for higher crop productivity. Understanding how plants respond to these challenges requires insights beyond whole-tissue or bulk gene expression studies. By enabling the analysis of gene expression at the single-cell level, single-cell transcriptomics has revolutionised our understanding of cellular heterogeneity and function. This potent method has proven crucial in revealing the intricate cellular diversity and regulatory networks that support a variety of biological activities. Single-cell transcriptomic methods, which were first created for animal systems, are increasingly being applied to plant biology, offering previously unheard-of insights into plant physiology, development, and responses to environmental cues.

What is Single-Cell RNA Sequencing?

"It is an advanced transcriptomic technology that analyses gene expression at the resolution of individual cells". Unlike conventional RNA sequencing, scRNA-seq reveals cell-to-cell variation, identifies rare cell types, and uncovers cell-specific regulatory networks. In agriculture, scRNA-seq has emerged as a powerful tool to study plant development, stress responses, nutrient uptake, and

crop improvement. This technology is transforming agricultural research by enabling precision breeding and targeted genetic interventions. scRNA-seq targets the genome of individual cells from a cell population. scRNA-seq can capture the transcriptomic profile of individual cells. This enables the identification of cellular heterogeneity and provides insights into cell differentiation, tissue development, and responses to environmental cues. Assess transcriptional similarities and differences within a population of cells. Identify rare cell populations (Tang *et al*., 2009).

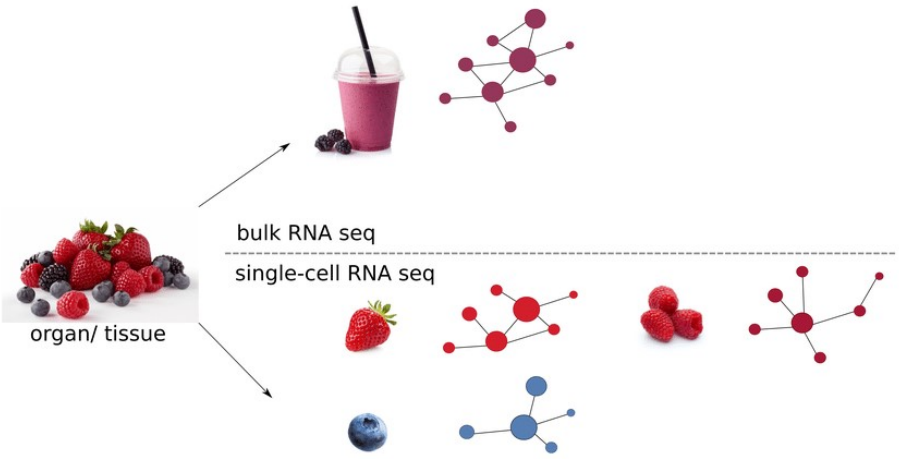


Fig.1. Difference in resolution between bulk and single-cell RNA-seq data at the level of gene networks. Sequencing inputs are illustrated as different fruits (left), which become homogenized into a mixed source material for bulk RNA-seq, analogous to a fruit smoothie (top) (Steinheuer et al., 2021).

Bulk RNA-seq only provides information on the average gene expression of the sample and can hide important cells. In contrast, scRNA-seq allows the dissection of transcriptional heterogeneity among individual cells. A thorough understanding of transcriptome dynamics among diverse cell populations is made possible by scRNA-seq, which enables the analysis of gene expression at the level of individual cells. Rare cell kinds can be identified, cell-to-cell diversity can be described, and cellular responses to stimuli or perturbations can be explained at a level of detail never before possible thanks to this high-resolution method. Bulk RNA-seq, on the other hand, combines gene expression data from a whole sample, which might disguise sample heterogeneity and obscure the contributions of individual cell types (Wang *et al*., 2023).

Workflow of single-cell RNA sequencing

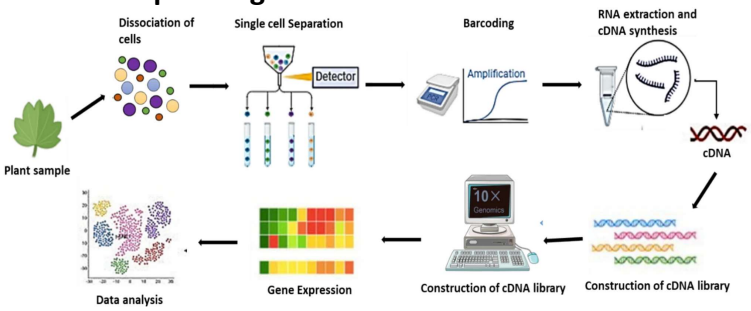


Fig. 2. Schematic Workflow of Single-Cell RNA Sequencing (scRNA-seq) in Plants (Singh *et al.*, 2024)

A crucial initial step in single-cell RNA sequencing (scRNA-seq) is single-cell isolation. Compared to animal systems, isolation is more difficult in plant cells because of their stiff cell walls. The main techniques are in Table 1.

Table 1. Overview of single cell isolation techniques (Hu *et al*., 2016)

Isolation techniques	Description	Advantage	Disadvantage
Fluorescence-Activated Cell Sorting (FACS)	Utilises fluorescent markers to sort cells by size, granularity, and fluorescence.	Enables high-speed, multiparametric analysis.	Requires a large quantity of cells and may cause cell damage due to high flow rates.
Magnetic-Activated Cell Sorting (MACS)	Employs magnetic beads conjugated with antibodies to isolate cells.	Provides a cost-effective and high-purity method.	Limited to surface markers and potential for non-specific binding.
Laser Capture Microdissection (LCM)	Utilises laser to isolate specific cells from solid tissue samples on a microscope slide.	Offers high precision and preserves tissue morphology.	Requires high skill and poses a risk of technical issues.
Microfluidics-Based Cell Isolation	Utilizes microchannels to manipulate fluids and isolate cells based on various properties.	Consumes low sample volumes and integrates well with other techniques.	Demands high skill for operation.
Manual Cell Picking	Combines micromanipulators with an inverted microscope to manually isolate single cells using micro-pipettes.	Enables the isolation of live cells.	Characterized by low throughput and requires high skill.

The conversion of the massive and intricate datasets produced by single-cell RNA sequencing (scRNA-seq) into biologically significant data requires bioinformatics. Bioinformatics is used in plant single-cell transcriptomics to analyse cellular responses, identify cell types, find marker genes, and rebuild developmental trajectories.

Table 2. Role and bioinformatics databases of used for Single-Cell Transcriptomics (Singh *et al*., 2024)

Role	Description	Key Databases and Tools
Data Acquisition and Preprocessing	Ensures high-quality raw data by filtering out low-quality reads, removing contaminants, and correcting sequencing errors	FastQC, Trimmomatic

Role	Description	Key Databases and Tools
Dimensionality Reduction and Clustering	Visualises high-dimensional data in 2D or 3D, and groups cells with similar expression profiles to identify distinct cell types and subpopulations	Seurat, SC3, PCA, t-SNE, UMAP
Differential Gene Expression Analysis	Identifies genes with significant expression differences between cell clusters to understand the functional roles of specific cell types	DESeq2, EdgeR
Pathway Analysis	Provides insights into biological processes and pathways enriched in different cell populations	GOseq, KEGG Mapper
Integrative Analysis	Correlates gene expression with other omics data, such as proteomics and metabolomics, for a comprehensive understanding of cellular functions	MOFA, Seurat v3
Handling Technical Noise and Batch Effects	Develops methods to account for and correct technical variations and batch effects in single-cell RNA-seq data	Combat, Harmony
Data Integration and Visualisation	Combines data from multiple sources and provides visualisation tools for intuitive understanding of complex datasets	Cell Ranger, Scanpy, Monocle

To date, there have been five single-cell transcriptome studies of plant species: 0*Arabidopsis thaliana, Oryza sativa*, Cotton, *Solanum lycopersicum*, and *Zea mays* (Sun *et al*., 2024).

Advantages of Single-Cell RNA Sequencing

- Identifies rare and specialised plant cells that may be overlooked in bulk sequencing.
- Reveals cellular diversity within complex plant tissues.
- Captures cell-to-cell variation in gene expression and cellular states.
- Dissects cellular heterogeneity by profiling individual-cell transcriptomes.
- Resolves cell-specific responses involved in plant growth, development, and stress adaptation.
- Overcomes limitations of bulk sequencing by providing high-resolution insights into plant cellular functions.

Limitations:

Despite its potential to provide high-resolution insights into plant transcriptomes, single-cell RNA sequencing (scRNA-seq) faces several technical and biological limitations:

- The rigid cell wall makes single-cell isolation difficult and often requires protoplast formation, which can damage or bias certain cell types.

- RNA amplification can introduce noise, amplification bias, and dropout, affecting gene expression measurements.
- Low-abundance transcripts may remain undetected, particularly in rare cell types.
- Cell isolation and processing may alter natural gene expression and cause loss of fragile or specialised cells.
- scRNA-seq requires specialised equipment, high sequencing costs, and advanced bioinformatics, which can limit experimental scale. (Lähnemann *et al*., 2022)

Achievements

- Revealed cell-specific responses to salt stress in rice (*Oryza sativa*) and identified stress-responsive genes and regulatory mechanisms.
- Uncovered cellular heterogeneity and developmental patterns in *Arabidopsis thaliana* roots.
- Characterised cell-specific transcriptional profiles in the maize (*Zea mays*) shoot apical meristem.
- Enabled the identification of rare and previously uncharacterised cell types in roots, leaves, and meristems.
- Provided opportunities for cell-specific targeting of stress-responsive genes, supporting the development of stress-resilient crops.
- Advanced high-resolution plant transcriptomics by revealing gene expression patterns that are masked in bulk tissue analysis (Wang *et al*., 2023).

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SMART DAIRY HOUSING: TECHNOLOGY-DRIVEN TRANSFORMATION OF INDIAN DAIRYING

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Abstract

Dairy cattle housing directly influences animal health, welfare, comfort and productivity. A "smart barn" can be understood as a housing system in which environmental or animal-level data are collected, processed and used to support management or automate selected actions. This article explains how conventional dairy housing can be enhanced with temperature and relative-humidity sensors, automated ventilation and cooling, accelerometers for behaviour monitoring, computer vision for posture and locomotion assessment, and electronic identification for individual animal records. The concept is illustrated through the pathway from data collection to human decision-making. Precision-livestock technologies have been increasingly studied in cattle production, although their validation, reliability and practical value vary among applications and production systems. Their application under Indian conditions requires consideration of heat stress, housing type, farm size, infrastructure, electricity, water availability and cost. The article concludes that a smart barn is not simply a technology-rich shed; its value depends on reliable information leading to an appropriate management response.

Keywords: Smart barn; environmental monitoring; cow comfort; precision livestock farming; Internet of Things (IoT)

Introduction

Housing is an important non-genetic factor affecting dairy cattle performance. The physical environment influences a cow's ability to rest, feed, drink, move and regulate body temperature. Inadequate lying space, unsuitable flooring, poor ventilation and excessive heat load can adversely affect cow comfort, health and productivity (Cook & Nordlund, 2004; Fregonesi *et al.,* 2007; Kadzere *et al.,* 2002). Heat load is particularly relevant to dairy production in warm climates because high-producing cows generate considerable metabolic heat and may experience reduced feed intake and milk production when environmental conditions become stressful (Kadzere *et al.,* 2002). Indian animal-husbandry advisories also identify heat stress as an important management challenge and recommend shade, ventilation, adequate water and appropriate cooling measures (ICAR, 2025; NDDB, n.d.).

Traditionally, housing management decisions have relied largely on stockperson experience and periodic visual assessment. This approach remains important, but sensor-based systems can provide more frequent information about both the housing environment and individual animals. Recent reviews show that precision technologies for cattle monitoring include inertial sensors, image/video systems and other sensing approaches, but the degree of validation varies across applications (Besler *et al.,* 2024). The question addressed in this article is whether dairy barns can be equipped

with sensing and automation technologies that provide objective information and whether that information can support practical management decisions.

What is a Smart Barn?

A smart barn can be understood as a housing facility in which environmental conditions, animal behaviour and equipment performance are monitored using sensors, with information processed to support management or automate selected actions (Berckmans, 2017; Halachmi *et al.,* 2019). It is important to distinguish a smart barn from a simply mechanised barn. A barn with electric fans and an automated scraper is mechanised. A barn in which fans respond automatically to measured environmental conditions is moving towards a smart-barn system. In practical terms, the distinction lies in the collection, processing and use of information for management, rather than in the presence of machinery alone.

A useful way to understand the concept is: Sense → Analyse → Detect → Alert → Assess → Act. Here, "detect" refers to identifying a deviation or condition of interest, whereas "alert" refers to communicating that information to the person responsible for management.

Environmental Monitoring

The housing environment can be characterised by temperature, relative humidity, temperature–humidity index (THI), air movement, ammonia concentration and light conditions. THI is widely used to describe heat load in dairy cattle, although the level at which heat stress becomes evident can vary with animal characteristics, production level and environmental conditions (Kadzere *et al.,* 2002). Therefore, a single THI value should not be treated as a universal biological threshold for every dairy cow.

Temperature and relative-humidity sensors can be placed at different locations within a barn to monitor variation in the microclimate. In long sheds, environmental conditions may differ between locations because of differences in air movement, shade and ventilation. Continuous or repeated measurements can therefore help identify areas where cooling or ventilation may need attention.

Air-quality monitoring can also be incorporated into smart housing, particularly in enclosed or poorly ventilated buildings. Sensors measuring ammonia can provide information about air-quality conditions and may help identify ventilation problems (Halachmi *et al.,* 2019).

Cow Behaviour and Comfort

Cow comfort is closely associated with lying behaviour. Dairy cows spend a substantial part of the day lying, although lying time varies with housing, management and animal factors (Tucker *et al.,* 2021). Overstocking can also reduce lying time, illustrating why resting-space management matters (Fregonesi *et al.,* 2007).

Accelerometers attached to the leg or neck can record activity and lying or standing patterns and provide individual-level information for health and management monitoring (Rutten *et al.,* 2013). Recent validation research emphasizes that sensor accuracy, bias and reproducibility need to be evaluated before measurements are treated as reliable indicators in farm decision-making (Lee *et al.,* 2025).

Feeding and drinking behaviour can also be monitored using automated systems. Rumination time measured with animal-mounted sensors can provide additional information relevant to feeding behaviour and health status (Rutten *et al.,* 2013; Halachmi *et al.,* 2019).

The practical value of behaviour monitoring lies in identifying deviations from an individual cow's normal pattern. A cow showing a sudden change in activity, lying behaviour or rumination may require closer observation. The sensor does not establish the cause; it provides information that can guide further assessment.

Smart Ventilation and Cooling

Heat stress is an important environmental challenge for dairy cattle in many parts of India. Under heat load, cows may reduce feed intake, alter their activity and increase water consumption, with consequences for production and welfare (Kadzere *et al.,* 2002; ICAR, 2025; NDDB, n.d.).

In a smart barn, environmental sensors can be connected with fans, sprinklers or other cooling equipment. When environmental conditions reach a predefined management level, the system can activate cooling equipment. Such automation allows cooling to respond to measured environmental conditions rather than operating continuously. Sensor-based control can therefore form part of a wider heat-abatement strategy, provided that the equipment is correctly installed, maintained and matched to the housing system.

For Indian farms, the practical value of automated cooling will depend on electricity availability, water supply, equipment cost, barn design and the ability to maintain the system. These constraints are especially important when technologies developed under other production systems are considered for Indian farms.

Computer Vision in Housing

Computer vision uses cameras and image-processing algorithms to extract information about animals and their environment. It is being investigated for monitoring posture, locomotion, body condition, behaviour and other measurable characteristics in cattle (Qiao *et al.,* 2021a, 2021b; Besler *et al.,* 2024). Recent reviews also describe non-contact sensing and image-based monitoring as active areas of precision-livestock research (Yin *et al.,* 2023).

The technology has potential for dairy housing because a camera can observe several animals without attaching a device to every cow. However, performance can be affected by lighting, animal density, camera position, occlusion, dirt and changes in the housing environment. Computer vision should therefore be regarded as an emerging tool for many housing applications rather than a universally validated solution (Besler *et al.,* 2024).

Camera-based systems may also help estimate how animals are distributed within a housing area. When adequately validated, such information could assist in identifying overcrowding, underused space or changes in animal movement patterns (Qiao *et al.,* 2021a).

Individual Animal Identification

Individual animal identification becomes essential when environmental or behavioural information is intended to be linked to specific cows. RFID ear tags or electronic identification systems can connect an animal with records of behaviour, feeding, health, production and reproduction (Berckmans, 2017; Rutten *et al.,* 2013).

This linkage is particularly important in precision livestock management. A temperature sensor may describe the barn environment, but an animal-identification system allows animal-level observations to be connected with the conditions experienced by a particular cow. The combination of identification and sensor data therefore provides the basis for individual-cow management.

In India, electronic animal identification and digital livestock records are also being developed through national livestock information systems. The Department of Animal Husbandry & Dairying reports the use of Pashu Aadhaar animal IDs and the Bharat Pashudhan platform, which includes animal management, health, breeding, nutrition, tag-management and digital livestock-census modules (DAHD, 2026). Their usefulness at farm level depends on reliable identification, data connectivity and integration with farm records.

From Sensor to Management Decision

The pathway from data collection to management action follows a logical sequence: Sense → Analyse → Detect → Alert → Assess → Act. A sensor measures a variable such as barn temperature, humidity or cow activity. Software processes the information and may compare it with a predefined management threshold or an individual animal's normal pattern. When a deviation is detected, an alert may be generated. The farmer or veterinarian then assesses the situation and decides whether action is required (Berckmans, 2017; Rutten *et al.,* 2013).

It is important to recognise that the system provides information, not automatically correct decisions. A temperature alert may indicate that cooling equipment needs attention, while an activity alert may require examination of the individual cow. Sensor malfunction can also produce misleading information. Human assessment therefore remains an important part of the smart-barn system.

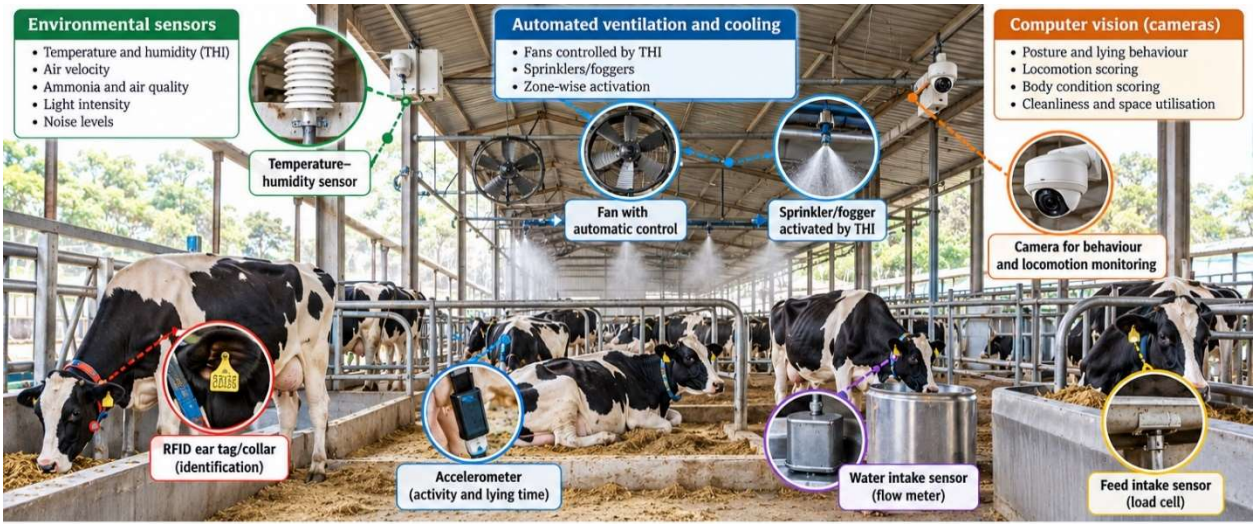


Figure 1. Smart dairy barn: integrating sensing, data and management

Table 1. Smart housing technology, information generated and possible management application

Technology	Information generated	Management application
Temperature–humidity sensor	Temperature and relative humidity; calculated THI	Monitor heat load and support cooling decisions
Accelerometer	Lying, standing and activity patterns	Identify cows requiring closer observation
Automated fan–sprinkler system	Environmental conditions and cooling response	Adjust cooling according to heat load

Technology	Information generated	Management application
RFID/electronic identification	Individual animal identity	Link animal with behaviour, health and production records
Camera/computer vision	Posture, locomotion, body condition and spatial distribution, depending on system validation	Support screening and housing assessment
Ammonia sensor	Ammonia concentration	Monitor air quality and support assessment of ventilation conditions
Water-flow/availability sensor	Water use and availability	Identify interruptions or abnormal water use

Can Smart Barns Work in India?

The answer depends on the production system. Many precision-livestock technologies have been developed and evaluated in intensive dairy systems. Their performance and economic value may differ under Indian conditions because climate, housing type, herd size, infrastructure, electricity availability, water supply and labour conditions differ. A recent scoping review of cattle-monitoring technologies found substantial variation in technology types, monitoring goals and levels of validation across studies (Besler *et al.,* 2024).

For large organised and institutional dairy farms, environmental monitoring, automated cooling, electronic identification and selected animal-monitoring technologies may be practical where appropriate infrastructure is available. For smallholder farms with a few animals, simpler approaches may be more appropriate. These could include a low-cost temperature–humidity sensor, a simple heat-stress warning system or digital recording of individual animal information.

The most valuable technology is not necessarily the most complex one. It is the one that provides reliable information leading to a management action that the farmer can realistically implement under local conditions.

Table 2. Smart Dairy Housing Technologies and Their Availability in India

S. No.	Smart technology in dairy housing	Application	What it monitors/automates	Firms available in India
1.	IoT environmental sensors	Real-time monitoring of barn environment	Temperature, RH, THI, air quality	Stellapps, IoT-based farm solutions
2.	Automated cooling systems	Heat-stress management	Fans, sprinklers, misters/foggers	Dairy automation/IoT providers
3.	RFID/electronic animal identification	Individual animal identification	Identity, movement, production and management records	Stellapps, Afimilk, Nedap
4.	Smart neck collars/wearable sensors	Continuous animal monitoring	Activity, rumination, temperature, behaviour	JioGauSamriddhi, Areete/Ayushman Cowfit, Afimilk

S. No.	Smart technology in dairy housing	Application	What it monitors/automates	Firms available in India
5.	Heat/estrus detection	Reproductive management	Activity and behavioural changes	JioGauSamriddhi, Prompt DairyTech, Afimilk, eVerse.AI
6.	Rumination monitoring	Early health and feeding assessment	Rumination behaviour	JioGauSamriddhi, Areete, Afimilk
7.	Animal body-temperature monitoring	Health and heat-stress monitoring	Body temperature	Areete/Ayushman Cowfit, wearable IoT systems
8.	GPS/location monitoring	Animal movement and management	Location and movement	Areete/Ayushman Cowfit
9.	AI-based computer vision	Contactless animal monitoring	Behaviour, posture, lameness, body condition	Emerging/research-stage solutions in India
10.	Thermal imaging	Non-contact health monitoring	Surface-temperature patterns	Emerging/research applications
11.	Automated feeding systems	Precision feeding and labour reduction	Feed delivery and individual/group feeding	Afimilk, GEA, Dairymaster, Trioliet
12.	Automated milking systems	Reduces manual milking	Milk yield, frequency etc	Afimilk, MSD, SEFA, DeLaval, InterPuls, Waikato,YantraDairy
13.	Cloud-based dairy management	Centralized farm records	Animal, production, health and environmental data	Stellapps, MSD DataFlow II, Afimilk
14.	AI/ML decision-support systems	Data-driven management	Health, reproduction, production and risk prediction	Stellapps, Nitara, emerging AI systems
15.	Digital animal health management	Early detection and health records	Health events, treatments and alerts	Areete, MSD/Allflex, Nitara
16.	Smart herd-management software	Integrated dairy management	Animal, reproduction, health and production records	Afimilk, Stellapps, GormalOne, BouMatic, Lely, Herdwatch, MSD

Limitations and Practical Considerations

Several practical challenges must be considered. Sensors require calibration, maintenance and appropriate placement. Dust, moisture, dirt, sunlight and other environmental conditions can affect sensor performance (Neethirajan, 2020). False alerts caused by sensor errors or inappropriate thresholds can reduce farmer confidence in the system.

Equipment cost is another important consideration. A comprehensive system involving environmental sensors, animal-mounted devices, automated ventilation and data-management software may require substantial investment and may not be justified for every farm. Power interruptions and connectivity problems can also affect data collection.

Data interpretation requires appropriate technical knowledge. Technologies developed in one production system should not automatically be assumed to perform similarly in another. Validation under Indian housing systems, climatic conditions and management practices is therefore necessary before widespread recommendations are made.

Future Scope

The future of smart dairy housing lies in the integration of environmental, behavioural, health and production information. A system could combine barn-level THI measurements with individual cow activity, lying behaviour, feeding and production records. Weather information could also be incorporated to support preparation for periods of high heat load.

Smart housing can extend beyond animal monitoring to include resources such as water availability, cooling-water use and electricity consumption. Monitoring these variables could help identify interruptions, abnormal use or equipment problems.

As sensor costs and digital connectivity improve, simplified smart-barn systems could become more accessible to a wider range of dairy farms. Recent reviews indicate continued expansion of precision-livestock research, while also highlighting the need for validation, standardisation and reliable interpretation of sensor data (Trapanese *et al.,* 2025; Lee *et al.,* 2025). Development for Indian farms should therefore be guided by evidence from Indian production conditions rather than direct transfer of technologies developed for substantially different housing systems.

Conclusion

Dairy housing can be equipped with sensors, automated equipment and data-processing systems that provide more frequent information about the environment and the animals. However, a smart barn is not simply a technology-rich shed. Its value depends on whether the information generated is reliable, whether it reaches the farmer in a usable form and whether it leads to an appropriate management response. Under Indian conditions, selective adoption of validated technologies, beginning with clearly defined problems such as environmental monitoring and heat-stress management, may be more practical than installing complex systems without a clear management purpose.

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SMART SEEDS FOR A CHANGING CLIMATE: HOW NANOTECHNOLOGY AND ARTIFICIAL INTELLIGENCE ARE RESHAPING SEED SCIENCE

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Introduction

Every crop begins its life as a seed, and the first few days after sowing often decide how well that crop will eventually grow. Climate change is making this early stage riskier than ever: rainfall is less predictable, heat waves arrive earlier in the season, and soils in many regions are becoming more saline because of poor irrigation practices and rising sea levels. Because of this, scientists working in seed science and technology are looking for new ways to make seeds tougher and smarter before they ever go into the ground. Two developments are leading this shift. The first is nano-priming, a pre-sowing treatment that uses tiny engineered particles to switch on a seed's internal defenses. The second is the growing use of artificial intelligence (AI) to sort, test, and even design seed treatments with far greater precision than manual methods allow. This article examines both technologies in detail, explains how they work together, and discusses the opportunities and challenges they present for modern agriculture.

The discussion that follows is organized to move from the biological basis of seed priming, through the specific evidence supporting nano-priming in different crops, into the digital tools that are transforming seed testing and certification, and finally into the practical, environmental, and policy questions that will decide how quickly these technologies reach ordinary farmers.

The Global Challenge: Climate Change and Seed Systems

Food security depends on the reliable performance of seeds under increasingly variable field conditions. Seed germination and early seedling growth are widely regarded as the most climate-sensitive stages of a crop's life cycle, since young seedlings have limited root systems and little stored energy to draw on if conditions turn unfavourable (Reed *et al.*, 2022). A short dry spell or an unexpected heat event during germination can significantly reduce final plant stands, even if conditions later in the season are normal. Traditional plant breeding, which focuses on improving a crop's genetics over many generations, is important but slow, often taking a decade or more to release a new variety suited to a changing climate. Seed technology offers a faster, complementary route: rather than waiting for new genetics, treatments can be applied to existing seed lots to help them cope better with the stresses they are likely to face at sowing time (Gohari *et al.*, 2025). This is one of the reasons nano-priming and AI-based seed management have attracted so much research attention in the past five years.

Seed Priming

Seed priming is not a new concept. Farmers and researchers have soaked seeds in water or nutrient solutions for decades to speed up germination, a technique that traces back to early experiments by Charles Darwin on lettuce and cress seeds in seawater, and was later formalized as a scientific

method by Heydecker and colleagues in 1973 (Aggarwal *et al.*, 2025). Over time, several distinct priming approaches have been developed. Hydro-priming involves simply soaking seeds in water before drying them again, while osmo-priming uses a controlled osmotic solution, often containing salts such as potassium nitrate, to regulate how much water the seed absorbs. Bio-priming introduces beneficial microorganisms onto the seed surface, which can protect against soil pathogens and improve nutrient uptake. The most recent addition to this list is nano-priming, which uses engineered nanoparticles instead of ordinary chemicals or microbes (Gohari *et al.*, 2025).

What makes nano-priming different from these older methods is not just the material used but the depth of biological change it can trigger. Because nanoparticles are so small, typically less than 100 nanometers in at least one dimension, they can cross biological barriers within the seed that larger particles simply cannot pass through. This allows them to interact more directly with the embryo and its surrounding tissues, producing effects that go well beyond a simple increase in water uptake.

Nano-priming

1. How nanoparticles enter and act within the seed

Nano-priming works by coating seeds with extremely small particles of elements such as zinc, silicon, copper, or silver, or with nanoparticles built from carbon-based materials. Once these particles reach the seed coat, some are absorbed into the tissue, where they can interact directly with the embryo, triggering biochemical responses that a normal soak in water cannot achieve. Once inside, the nanoparticles help deliver nutrients and signalling molecules straight to the developing plant, encouraging faster and more uniform germination as well as stronger, more vigorous seedlings (Bandeppa *et al.*, 2019).

2. The Antioxidant Connection

A central reason nano-priming improves stress tolerance lies in its effect on the seed's antioxidant system. Under stress conditions such as drought or salinity, plant cells accumulate reactive oxygen species, unstable molecules that damage membranes, proteins, and genetic material if left unchecked. Nanoparticles are known to activate antioxidant enzymes, including superoxide dismutase, catalase, and peroxidase, which help the plant neutralize these harmful molecules before they cause lasting damage (Aggarwal *et al.*, 2025). This reduces cell damage and allows the seedling to grow normally even when water or nutrients are scarce, which explains why nano-primed seedlings often show visibly greener leaves and longer roots than untreated ones under stress.

3. Green and Bio-Based Nanoparticles

A growing concern with early nano-priming research was that many of the nanoparticles tested were synthesized using industrial chemical processes, raising questions about cost, energy use, and potential toxicity if they accumulated in soil over repeated growing seasons. In response, researchers have increasingly turned to green, or bio-based, nanoparticles synthesized from plant extracts, fungal cultures, or agricultural waste rather than harsh chemical reagents. These bio-based particles are seen as a more environmentally friendly alternative and may ease some of the safety concerns associated with metal-based nanoparticles, while still delivering many of the same germination and vigor benefits (Aggarwal *et al.*, 2025).

Evidence from the Field: Crop-wise Case Studies

Laboratory findings are only useful if they hold up under real growing conditions, and a growing body of field research supports the benefits of nano-priming across several major crops. A recent

trial on field pea seeds tested three different nanoparticle blends, containing combinations of cobalt, manganese, copper, iron, zinc, molybdenum, selenium, calcium, silicon, boron, and sulfur, and found that all of the treatments improved seed quality and early seedling growth under both normal and drought-simulated conditions, although the exact mechanism varied depending on the specific blend used (Pavlović *et al.*, 2024). This is a particularly useful finding because it shows that nano-priming benefits are not limited to a single nanoparticle type, but can be achieved through several different formulations, giving researchers flexibility when adapting treatments to local soil and climate conditions.

Similar improvements have been reported in wheat and tomato, two crops that are staples in very different farming systems, reinforcing the idea that nano-priming is not limited to one crop type but can be adapted across many species and cropping systems (Gohari *et al.*, 2025). Wheat trials have generally focused on drought and salinity tolerance, given the crop's importance in semi-arid regions, while tomato studies have looked more closely at seedling vigor and early fruit-set outcomes. Taken together, these results suggest that nano-priming protocols will likely need to be fine-tuned crop by crop and even variety by variety, which is precisely the kind of large-scale optimization problem that artificial intelligence is well suited to help solve.

Artificial Intelligence in Seed Testing and Certification

While nano-priming changes what happens inside the seed, artificial intelligence is changing how seeds are evaluated and managed before they ever reach the field. Traditional seed testing relies on trained technicians manually inspecting samples for size, colour, shape, and germination rate, a process that is slow, labour-intensive, and can vary from one inspector to another depending on experience and fatigue.

Imaging and Spectroscopy-Based Quality Assessment

AI-based systems replace much of this manual work with high-resolution cameras, hyperspectral and near-infrared sensors, and machine-learning algorithms that can scan large numbers of seeds quickly and predict their viability and vigor with high accuracy, offering a level of consistency that manual grading cannot match (Rani *et al.*, 2021). A recent review of machine learning applications in seed science documents a wide range of successful examples, including deep-learning models that classify soybean seed quality from spectral and image data, near-infrared spectroscopy systems that assess wheat kernel vigor, and neural network approaches that distinguish viable from non-viable seeds across crops such as maize, alfalfa, and muskmelon, often reaching classification accuracies above ninety percent (Barad *et al.*, 2024). Hyperspectral imaging studies specifically on wheat have shown that seed viability can be reliably predicted from reflectance data captured from both sides of the kernel, without damaging or destroying the seed in the process (Zhang *et al.*, 2018). Because these methods are non-destructive, they allow seed companies to test far larger samples than destructive laboratory germination tests would normally permit, improving the statistical confidence of quality certification.

AI Adoption in the Indian Seed Sector

The Indian seed sector offers a useful real-world example of how these tools are being adopted at scale. According to Patel (2025), AI is being applied across the Indian seed sector to speed up the breeding of new crop varieties, improve the accuracy of seed quality testing, streamline seed distribution, and give farmers personalized, data-driven advice through precision agriculture tools. This work highlights that organizations such as ICRISAT, CropIn, and the Indian Council of Agricultural

Research (ICAR) are already applying AI to predict crop diseases, monitor fields in real time, and support timely farmer recommendations, even though gaps in rural infrastructure and inconsistent data quality remain obstacles to wider adoption (Patel, 2025). This pattern mirrors what is being observed elsewhere in seed science: AI and image-recognition tools are increasingly able to identify fine structural details in seeds, such as cotyledon number or seed coat integrity, quickly and without the errors that come from manual inspection, which strengthens both certification and quality-assurance processes (Patel, 2025). More broadly, ongoing work on the modernization of seed science and the seed industry frames digital technologies, alongside biotechnology and molecular breeding, as one of the core forces reshaping how seed quality, genetic diversity, and distribution are managed worldwide (Patel *et al.*, 2026).

AI-Guided Nano-priming Pipelines

The real promise for the future lies in combining nano-priming with AI rather than treating them as two separate, unrelated tools. In an integrated system, AI-driven imaging can first scan a batch of seeds to identify which ones are healthy enough to prime and which nanoparticle formulation and concentration would suit that particular seed lot best. This turns nano-priming from a one-size-fits-all treatment into a targeted, data-informed process, similar in spirit to how precision medicine tailors treatment to an individual patient rather than applying the same protocol to everyone.

At the same time, machine-learning models trained on germination outcomes can continuously refine these recommendations, effectively learning which nanoparticle combinations work best for which crop, soil type, or climate condition over successive growing seasons. As more field data accumulates from trials such as those on pea, wheat, and tomato, these models should, in principle, become steadily more accurate at predicting outcomes before a single seed is sown (Pavlović *et al.*, 2024; Barad *et al.*, 2024). Pairing greener, bio-based nanoparticle materials with AI-guided application could make seed treatment both more precise and more environmentally sustainable at the same time, addressing two of the biggest criticisms levelled at earlier generations of chemical seed treatments (Aggarwal *et al.*, 2025).

Environmental, Safety, and Economic Considerations

Despite the promise, several challenges stand in the way of widespread adoption. Nanoparticles do not behave the same way across all crop species, and a treatment that works well for one plant may have little effect, or even a mildly negative one, on another, which means results cannot always be generalized from one crop to the next (Gohari *et al.*, 2025). Long-term safety data on how nanoparticles behave once they enter soil and, potentially, food chains is still limited, and this understandably raises valid questions among regulators, farmers, and the public about how quickly these treatments should be scaled up commercially.

On the AI side, building and deploying accurate seed-scanning systems requires investment in cameras, spectroscopic sensors, computing infrastructure, and trained personnel, costs that can be difficult for smaller seed companies or under-resourced regions to absorb (Patel, 2025). Data quality is another concern raised repeatedly in the literature: machine-learning models are only as good as the data used to train them, and inconsistent record-keeping or a lack of standardized testing protocols in many seed-testing labs can limit how well these tools perform once deployed outside a research setting (Barad *et al.*, 2024).

Policy and Infrastructure Considerations

Technology alone cannot guarantee adoption. Extension services, government seed certification agencies, and private seed companies all need to coordinate if AI-integrated nano-priming is to

move from research trials to everyday farming practice. In India, public-private partnerships and government digital-agriculture initiatives are already being credited with accelerating early adoption of AI tools in the seed sector, even as rural connectivity and inconsistent data quality continue to slow progress in some areas (Patel, 2025). Similar coordination will likely be needed elsewhere: regulatory frameworks for nanomaterials in agriculture are still evolving in most countries, and clear labelling and safety standards will be important for building farmer and consumer trust as nanoprimed seed products move toward commercial markets (Gohari *et al.*, 2025).

Future Outlook

Looking ahead, several research directions seem likely to shape the next stage of this field. First, larger and more standardized field datasets, covering multiple crops, soil types, and climate zones, will be needed to train AI models that can reliably recommend nano-priming protocols outside of controlled laboratory conditions. Second, continued work on green nanoparticle synthesis should help address environmental and safety concerns while keeping production costs manageable for smaller seed enterprises (Aggarwal *et al.*, 2025). Third, closer collaboration between plant physiologists, materials scientists, and data scientists will be needed to move from correlational findings, where a treatment is observed to work, toward mechanistic understanding, where researchers can explain precisely why it works and predict how it will perform in new situations. Finally, as tools such as hyperspectral imaging and deep learning become cheaper and more accessible, it is likely that mid-sized seed companies, not just large multinational firms, will be able to adopt at least basic versions of AI-based quality screening, broadening the reach of these technologies (Barad *et al.*, 2024; Patel, 2025).

Conclusion

Seed science is entering a period of rapid change. Nano-priming gives seeds a biochemical head start against drought, salinity, and heat, while artificial intelligence brings speed, consistency, and precision to testing, sorting, and matching seeds with the right treatment. Neither technology alone solves the problem of feeding a growing population on an increasingly unpredictable planet, but together they represent one of the most exciting frontiers in modern agriculture. Evidence from field trials on pea, wheat, and tomato, together with real-world adoption stories from the Indian seed sector, shows that these tools are already moving beyond the laboratory and into practical use (Pavlović *et al.*, 2024; Patel, 2025). As research continues to address safety, cost, and infrastructure gaps, AI-integrated nano-priming has the potential to become a standard part of seed technology, helping farmers grow reliable crops even as the climate around them continues to change.

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SPEED BREEDING: ACCELERATING THE FUTURE OF CROP IMPROVEMENT

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Abstract
Global agricultural productivity and food security are threatened by climate change, the growing world population, and the difficulties posed by the pandemic era. To overcome these challenges and meet food requirements, breeders have applied and implemented different advanced techniques that accelerate plant development and increase crop selection effectiveness. There is an urgent need for redesigning crops for climate resilience and sustainable yield and nutrition. The rate of crop improvement is largely impeded by the long generation time taken by crop plants during the breeding process. As a solution in this direction, speed breeding is now being practiced at a large scale to reduce generation time to accommodate multiple generations of crops per year. Researchers have developed speed breeding protocols for various crops, enabling the cultivation of multiple generations within a single. To enhance the efficiency of breeding, researchers are now adopting an integrated approach where speed breeding is used along with modern plant breeding and genetic engineering technologies.

Keywords: Speed Breeding, Genetic Engineering, climate resilience

Introduction

The growing human population and a changing environment have raised significant concern for global food security. According to an estimate, by 2050, we need to produce 60-80% more food to sustain 10 billion people. Therefore, scientists are prompted to develop efficient methods and strategies to give impetus for future breeding programmes and ultimately increase crop yield and productivity in a short period (Hickey *et al.,* 2019).

Speed breeding: It is a technique used in crop improvement that accelerates the plant breeding cycle by manipulating environmental factors to promote rapid growth and development. Used to increase agricultural yield by altering the light duration, intensity, and temperature-controlled zone, as well as the generation of disease-resistant varieties, lowering salt sensitivity in crops and many more.

Comparison of speed breeding with other breeding techniques

Plant breeding strategies that use existing genomic variation in plants to generate a variety in eight to ten years can reduce genetic variability in the genome of the plant. Traditional breeding methods cannot meet the ever-increasing food demand for grain crops.

Dr. Lee Hickey and his team at the University of Queensland started developing speed breeding protocols for various crops in 2001. First published results demonstrate the successful application of speed breeding in wheat in 2007.

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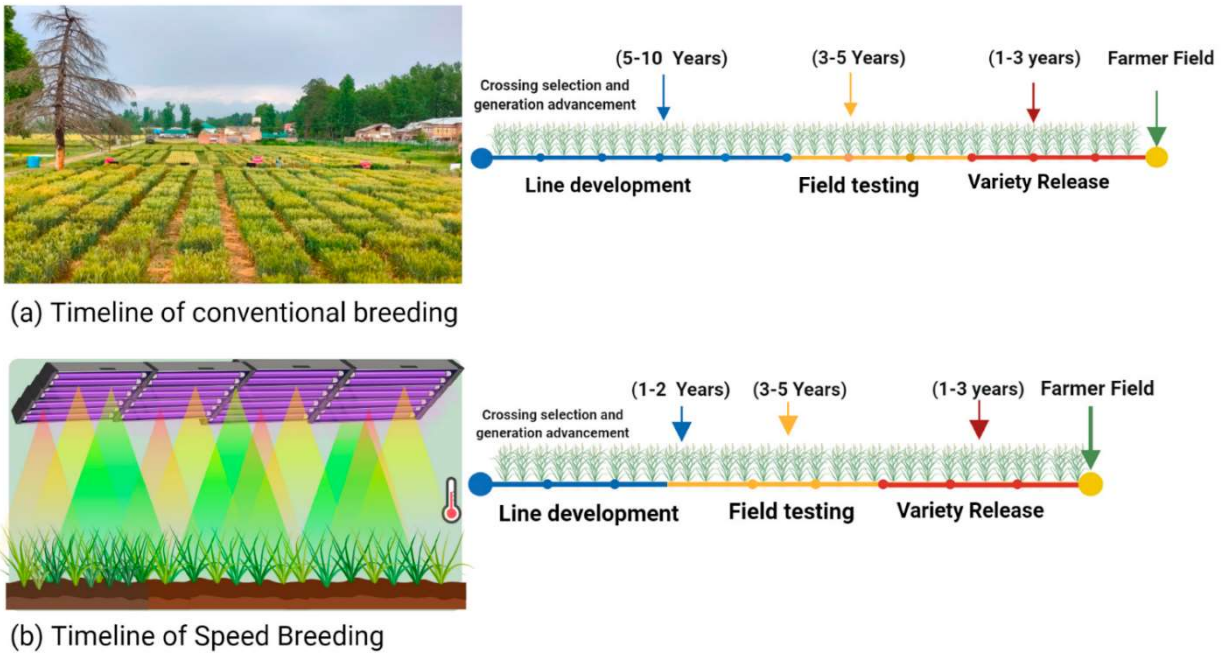


Fig. 1. Timelines of varietal development with (a) conventional breeding and (b) speed breeding (Samantara et al., 2022)

Components of speed breeding (Begna, 2024)

1. Photoperiod and light: Through phytochromes, plants sense and react to red and far-red light; through cryptochromes and phototropins, they perceive and react to blue light.

2. Temperature and humidity

a) Temperature: Optimum air and soil temperature are key factors to achieve satisfactory germination, seedling establishment and proper vegetative and reproductive growth.

b) Humidity: 60-70% was suitable for most of the crops; however, those crops that adapted to dry zones require less humidity. (Ghosh *et al*., 2018).

3. Carbon dioxide (CO_2):

In some plants, higher levels of carbon dioxide (CO_2) may speed up plant growth and accelerate the shift from the vegetative to reproductive stages.

Molecular pathways involved in speed breeding technique:

1. Photoperiod and Light Quality Regulation

Extended photoperiods (e.g., 20-22 hours of light) and specific light spectra (notably red and far-red light) are central to speed breeding.

2. Circadian Clock Components:

Extended photoperiods can modify plants' internal clocks. Understanding circadian regulation is crucial for optimizing speed breeding protocols.

3. Florigen Pathway

Genes like *FT (Flowering Locus T)* play crucial roles in determining flowering time. Speed breeding can alter the expression of these genes (Bar *et al*., 2014).

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Types of speed breeding

Speed breeding I - Controlled-environment chamber speed breeding

A Conviron BDW (walk-in controlled growth chamber).

1. Speed breeding II - Glasshouse speed breeding conditions

Glasshouse speed breeding conditions

A temperature-controlled glasshouse fitted with high-pressure sodium vapour lamps (22 hours photoperiod)

2. Speed breeding III - Homemade growth room design for low-cost speed breeding

Homemade growth room design for low-cost speed breeding

A room of 3m × 3m × 3m with insulated sandwich paneling fitted with seven LB-8 LED light boxes (Watson *et al*., 2018).

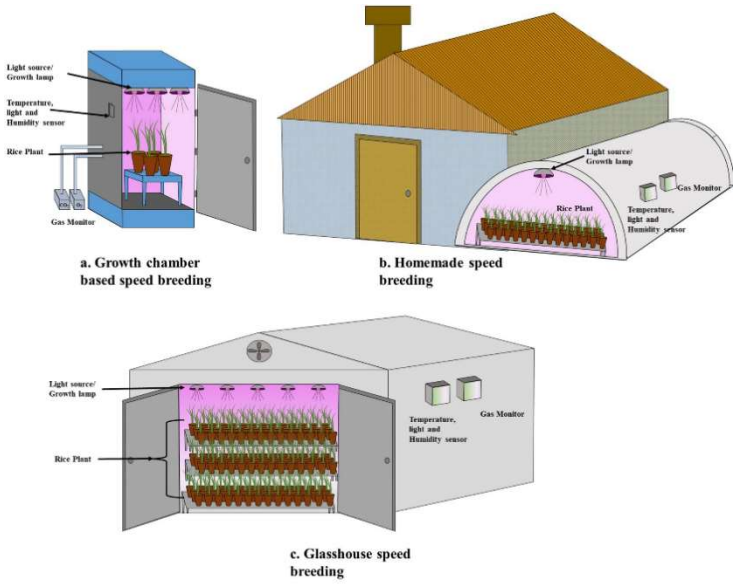


Fig. 2. Illustration depicting a different kind of structural set-up used for speed breeding of food and industrial crop plants (Sharma et al., 2023)

Achievements of Speed breeding in India

1. ICPV 25444 (First speed breeding variety released in India)

- Heat-tolerant pigeonpea (ICRISAT, Hyderabad)
- Enables 4 generations per year
- Matures in just 125 days and stands up to 45℃ summer heat

2. IRRI- Speed Flower: New rice variety under development

- Aim to fast-track the breeding of a high-yielding, climate-resilient, and nutritionally superior one.

Speed breeding facilities in India

1. IRRI South Asia Regional Centre (ISARC), Varanasi, Uttar Pradesh (Rice)
2. Tamil Nadu Agricultural University (TNAU), Coimbatore, Tamil Nadu (Rice and Wheat)
3. National Agri-Food Biotechnology Institute (NABI), Mohali, Punjab (2024)
4. ICRISAT, Hyderabad (Chickpea, Pigeonpea, Fingermillet and Pearl Millet)

5. Punjab Agricultural University (PAU), Ludhiana, Punjab (Rice and wheat)

Advantages of Speed Breeding

1. Shorter breeding cycles (2-6 generations per year).
2. Cost-effective in the long term.
3. Facilitates rapid phenotyping and genetic analysis.
4. Can be combined with CRISPR/Cas9 and genomic selection.
5. Large populations can be handled
6. Reduced maintenance cost of developing inbred lines
7. Maintains a high degree of homozygosity

Limitations of speed breeding

1. Short day plant required limited photoperiod for their growth and development, which limits the application of speed breeding for improvement short day vegetable crops.
2. Different phenotyping: speed breeding accelerates rapid cycling and shortens generation time further; early harvest of immature seed can interfere with phenotyping of some traits.
3. High initial investment: requires high initial investment, purchasing lighting equipment and controlled capabilities and supplementary LED lighting
4. Plants which are grown in an enclosed glass chamber with extended photoperiod show various physiological and toxicity symptoms like necrosis and yellowing due to any micronutrient or heavy metal deficiency or excess (Samantara *et al*., 2022)

Applications of Speed Breeding:

1. Accelerating the crop improvement selection programmes:
2. Speeding up the process of genomics.
3. An ideal method for generating large breeding populations
4. For boosting transgenic and CRISPR pipelines
5. Integrated phenotyping with speed breeding as a tool for improving yield
6. Gene editing in combination with speed breeding for crop improvement
7. Boosting genetic gain by speed breeding and genomic selection
8. Speed breeding to accelerate domestication
9. Multiple disease resistance by speed breeding

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SPICING UP TRADITION: INNOVATION IN ETHNIC AND REGIONAL CUISINES FOR THE MODERN CONSUMER

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Abstract

Traditional and regional cuisines are more than food; they are expressions of culture, agricultural heritage and generations of culinary knowledge. As consumer lifestyles and preferences change, there is growing interest in making these foods more convenient, innovative and relevant without losing their authentic character. This article explores how traditional recipes, regional spices and distinctive flavours can be adapted into modern formats such as ready-to-eat, ready-to-cook, instant and value-added foods. Advances in food processing and packaging can further improve safety, consistency and shelf life while preserving the sensory qualities that define traditional foods. Such innovation also creates opportunities for value addition to local agricultural produce, rural entrepreneurship, small food businesses and wider market access. At the same time, emerging trends such as clean-label products, functional ingredients, plant-based foods and premium regional flavours are opening new avenues for traditional cuisines. The future lies not in replacing tradition, but in giving it a modern expression preserving the taste, identity and stories of traditional foods while making them accessible and appealing to today's consumers.

Keywords: Ethnic cuisines, Regional foods, Spice innovation, Flavour innovation, Traditional foods, Food processing, Value addition, Culinary heritage, Food entrepreneurship, Consumer preferences.

Introduction

The evolution of ethnic and regional cuisines is about finding the right balance between preserving culinary heritage and meeting the changing expectations of modern consumers. Traditional foods reflect the culture, history, local ingredients and knowledge passed down through generations, while today's consumers increasingly look for convenience, new flavours, health benefits and authentic food experiences. This has created exciting opportunities to transform traditional recipes, spice blends and regional flavours into modern formats such as ready-to-eat, ready-to-cook, instant and value-added products without losing their original identity. Such innovation not only keeps traditional foods relevant to younger generations and global markets but also creates opportunities for value addition, entrepreneurship and better utilization of local agricultural resources. Thus,

bringing tradition and innovation together can help preserve cultural identity while giving traditional foods a new place in the modern food landscape.

Ethnic and Regional Cuisines

Ethnic and regional cuisines are much more than a collection of traditional recipes; they represent the culture, history, environment and agricultural identity of a community. Local climate, geography, availability of ingredients and generations of culinary knowledge shape the distinctive flavours, preparation methods and food practices of each region. For example, indigenous snacks of Northeast India, including *Sel roti* and *Khapse*, reflect the region's unique food traditions and adaptation to its geographical and climatic conditions. These foods also serve as an important means of preserving local culinary knowledge and cultural identity for future generations (A & Bhutia, 2025).

Similarly, Indonesian foods such as *rica-rica* and *sambal roa* demonstrate how regional dishes can carry meanings beyond taste and nutrition. Their characteristic spicy flavour is closely associated with local food culture, while the symbolism of spiciness has been linked to the challenges and experiences of life (Mardiana *et al*., 2026; Angelina *et al*., 2025). Such examples highlight the emotional and cultural value embedded in ethnic foods. As consumers increasingly seek authentic and meaningful food experiences, these traditional cuisines offer valuable opportunities for innovation and commercialization while retaining their distinctive regional identity.

Spices: The Essence of Regional Cuisine

Spices are at the heart of regional cuisines, shaping the distinctive taste, aroma, colour and character of traditional foods. Their use is often closely connected with the agricultural resources and culinary practices of a particular region, making them an important part of local food identity. For example, *rica-rica*, a traditional Indonesian preparation, is recognized for its characteristic chilli-based heat, which forms an important part of its sensory identity and distinguishes it from other regional dishes (Mardiana *et al*., 2026). The intensity and combination of spices not only influence the eating experience but also contribute to the uniqueness and recognition of a traditional cuisine.

The importance of locally sourced spices is also evident in *sambal roa*, where regional ingredients and traditional spice combinations contribute to its characteristic flavour and consumer appeal (Angelina *et al*., 2025). Such examples demonstrate that spices are not simply ingredients added for seasoning; they carry the identity and story of a region from one generation to another. At the same time, this strong connection between spices and regional identity provides an excellent foundation for developing innovative products that retain familiar traditional flavours while presenting them in convenient and contemporary formats.

Spice and Flavour Innovation

Spice and flavour innovation is becoming an important way of bringing traditional Indian foods into the modern food market. As lifestyles become busier, consumers increasingly look for convenient foods that can be prepared quickly without losing the familiar taste and aroma of traditional preparations. This has encouraged the development of convenient and processed versions of Indian traditional foods, supported by advances in food processing and mechanization (Basak *et al*., 2023).

Innovation, however, is moving beyond convenience towards functionality and added value. Indian spices such as turmeric and cinnamon contain phenolic and other bioactive compounds and are increasingly being explored as functional ingredients in food products (Kumar *et al*., 2025). A

particularly relevant example is the traditional Indian pickle. Traditional Indian pickles provide an excellent example of how spice combinations can contribute not only to flavour but also to food preservation. Kishoore *et al*. (2026) demonstrated that bioactive compounds such as curcumin, piperine and capsaicin are released from turmeric, black pepper and chilli during pickling, with interactions among spices influencing their release. The study further linked the controlled release of these spice bioactives with antioxidant activity and the characteristic long shelf life of Indian pickles. Thus, spice innovation is not simply about creating new flavours; it is about retaining the sensory identity of traditional foods while adding convenience, functionality, shelf stability and greater market value.

Traditional Foods in Modern Formats

Modernizing traditional foods is not about changing their identity; it is about presenting familiar foods in forms that suit the pace and preferences of today's consumers. Busy lifestyles have increased the demand for foods that are convenient, easy to prepare and available throughout the year, creating opportunities to transform traditional recipes through improved processing, packaging and marketing. This can also help traditional foods compete with commercially popular convenience and fast-food products. For example, the modernization of *Sombu corn* in Manggarai Regency illustrates how improvements in processing and marketing can increase the appeal and competitiveness of a traditional food while retaining its cultural connection (Paur *et al*., 2024).

A similar approach can be seen in the development of frozen, canned and other shelf-stable forms of traditional dishes, which make regional foods easier to store, transport and consume beyond their original geographical boundaries (Mardiana *et al*., 2026). Such innovations can help traditional foods reach younger consumers and new markets without losing their distinctive flavours and cultural character. In the Indian context, this approach offers considerable scope for transforming foods such as regional gravies, spice mixes, snacks, pickles and traditional meal preparations into convenient modern products. The real opportunity lies in making traditional foods easier to enjoy, while ensuring that convenience does not come at the cost of authenticity.



Fig. 1: From Culinary Heritage to Modern Innovation

Role of Food Processing and Packaging

Food processing and packaging play a crucial role in taking traditional Indian foods beyond their local markets and making them suitable for modern lifestyles. Advances in mechanization, controlled processing and preservation can improve consistency, safety and shelf life while retaining the characteristic sensory qualities of traditional products. For example, *Rogan josh*, a traditional Kashmiri meat curry, has been successfully developed as a ready-to-eat product in retort pouches. Retort processing enabled the product to remain microbiologically safe and sensorially acceptable for up to 12 months at ambient temperature, demonstrating how modern processing can convert a regional dish into a convenient, shelf-stable food product (Shah *et al*., 2017).

Packaging is equally important in protecting the quality of traditional foods during storage and distribution. In another Indian example, *peda*, a popular traditional dairy sweet, showed improved storage stability when appropriate barrier packaging and modified atmosphere packaging (MAP) were used; laminated plastic trays combined with MAP substantially delayed deterioration compared with conventional cardboard packaging (Rathod *et al*., 2023). These examples demonstrate that processing and packaging do not have to replace traditional food identity; instead, they can provide the technological support needed to preserve it, improve convenience and safety and make regional foods accessible to a much wider consumer base. Indian traditional foods similarly emphasize that mechanization, process control, preservation and packaging are important for meeting the growing demand for convenient traditional foods (Basak *et al*., 2023).

Opportunities for Agriculture and Entrepreneurship

Innovation in traditional foods can create valuable opportunities for farmers, food processors and rural entrepreneurs by turning locally available agricultural produce and spices into higher-value products. The development and commercialization of traditional foods such as *sambal roa* demonstrate how regional flavours can be transformed into marketable products with wider consumer appeal (Angelina *et al*., 2025). At the same time, encouraging young entrepreneurs to explore and modernize traditional foods can generate employment, support rural economies and help keep culinary traditions relevant for future generations. Thus, traditional food innovation can serve as a bridge between agricultural value addition, entrepreneurship and cultural preservation (Paur *et al*., 2024).

Conclusion

The future of ethnic and regional cuisines lies in balancing tradition with innovation. Modern processing, packaging and value addition can make traditional foods more convenient, safe and marketable while preserving their authentic flavours and cultural identity. By connecting culinary heritage with agriculture, entrepreneurship and modern consumer needs, India can give its traditional foods a stronger place in both domestic and global markets.

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SMALL GARDEN, BIG VISION: MRS VIMALA'S ORGANIC TEA STORY FROM THE KOTAGIRI HILLS

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On barely one and a half acres near Kotagiri, a woman grower has built a garden that feeds the soil and turns its leaves into green, oolong, and black tea.



Tea country wakes up slowly. Clouds settle on the ridges, the terraced slopes turn a deep green, and in a village near Kotagiri in the Nilgiris, Mrs Vimala is already among her tea bushes. She checks the young shoots and picks the tender leaves by hand.

Her garden is small, just **1 acre and 45 cents** (about 0.59 hectare). It has earned her recognition from the Tea Board of India.

An award on International Tea Day



On 21 May 2026, Tea Board India's South Zonal Office in Coonoor organised programmes and awareness activities to mark International Tea Day 2026. The aims were to promote Indian tea, create public awareness and recognise the contribution of small tea growers and other stakeholders in the sector. At the function, Mrs Vimala received the Progressive Small Tea Grower Award.

"Progressive" fits her. She grows tea in a way that gives back to the land, and she doesn't stop at selling green leaf.

Growing tea the organic way

Mrs Vimala's garden follows an organic nutrient management system and uses no synthetic fertilisers. Her methods were studied during an exposure visit, and the visit report describes them in detail.

Building the soil

- **Bury lapping.** Pruned material and plant debris are buried in the soil. As they decompose, they release nutrients, raise organic matter, boost microbial activity and help reduce erosion on the slopes.
- **Manuring pits.** A pit is provided after every three rows of tea. Organic manures go into the pits and are covered with soil, then break down over about six months, releasing nutrients gradually. This cuts nutrient losses and builds long-term fertility.
- **Dried elephant dung.** In the forest-fringe hills, elephant manure is a local resource. Dried and applied, it adds organic matter, improves soil structure and water-holding capacity, and releases nutrients slowly.

- **Wood ash.** Applied at **2 g per plant per month**, it supplies potassium, calcium and other minerals and helps keep the soil's pH balanced.

Keeping the ground covered

- **Weeds as mulch.** Instead of being thrown away, weeds and plant residues, including Datura, are laid around the bushes. The mulch conserves moisture, suppresses new weeds, keeps the soil temperature steady and adds organic matter as it decomposes.
- **Weeding every six months.** Timely weeding reduces competition for nutrients, water and light, and the weeds removed are recycled as mulch.

Liquid feeds for the plants

- **Jeevamritham**, made from cow dung, cow urine, jaggery, pulse flour and soil, acts as a microbial inoculant that raises beneficial microbes in the soil.
- **Panchagavya**, made from five cow-derived products, promotes vegetative growth and vigour and improves resistance to pests and diseases.
- **Meen Amilam (fish amino acid)** is applied at **500 ml in 10 litres of water**. Rich in amino acids, proteins and micronutrients, it supports shoot growth and nutrient uptake.

Pruning

Bushes are pruned regularly to keep their height and shape, encourage new shoots, improve air movement in the canopy, make plucking easier and remove diseased or unproductive branches.

Together, these practices keep the soil alive and the bushes vigorous. On steep slopes, where erosion and nutrient loss are constant worries, this soil-first approach matters especially.

From leaf to cup

Most small growers in the Nilgiris sell green leaf to factories. Mrs Vimala goes further. She makes **green tea, oolong tea and black tea** from her own leaf and sells them herself.

The three teas call for different skills. Green tea is barely oxidised, oolong is partly oxidised and black tea is fully oxidised, so each demands a different handling of the leaf. Selling finished tea also lets her keep more of the value that would otherwise go to others in the chain.

Why her story matters

Over 2.49 lakh registered small tea growers now contribute nearly 57% of India's total tea production, according to the Indian Tea Association. Most hold under two acres, and the Tea Board defines a small tea grower as anyone with up to 25 acres.

The Nilgiris are the largest tea tract in South India, covering about 43,000 hectares, and Nilgiri orthodox teas received Geographical Indication status in 2008. Small growers in the district mostly make CTC tea, so an organic grower crafting green, oolong and black teas stands out.

The theme of International Tea Day 2026 was "Sustaining Tea, Supporting Communities". Mrs Vimala's garden fits it: she sustains her soil through organic care, and her family and community through the teas she makes.

The lesson for other growers

Mrs Vimala's story says that size need not limit ambition. On a little under one and a half acres, organic management and value addition have brought her recognition. For small growers across the hills, she is an example of what a small holding can do.

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SUSTAINABLE MANAGEMENT OF WETLAND FISHERIES FOR LIVELIHOODS AND BIODIVERSITY CONSERVATION

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Introduction

Wetlands are highly productive ecosystems that support diverse aquatic biodiversity and provide essential ecological, economic and social benefits. Wetland fisheries are an important component of inland fisheries, particularly in floodplains, lakes, marshes, beels and other seasonally connected water bodies. These ecosystems provide feeding, breeding and nursery habitats for a wide variety of fish and other aquatic organisms. Wetland fish resources contribute significantly to food and nutritional security by providing affordable animal protein to rural and fishing-dependent communities. They also generate employment, income and livelihood opportunities for fishers, fish traders, processors and other associated groups. In many developing regions, local communities depend directly on wetland resources for their daily subsistence and economic activities. However, increasing anthropogenic pressure, including wetland conversion, habitat degradation, pollution, overfishing, hydrological alteration and invasive species, is threatening the productivity and biodiversity of wetland fisheries. Climate change further increases these pressures through changes in rainfall, flooding patterns, water temperature and hydrological connectivity. The degradation of wetlands can consequently affect both fish diversity and the livelihoods of communities dependent on these resources. Therefore, maintaining healthy wetland ecosystems is essential for sustaining fisheries production and biodiversity (Sarkar *et al*., 2020). Sustainable wetland fisheries management should integrate fishery development with habitat conservation, biodiversity protection and livelihood requirements. Community participation, scientific monitoring, appropriate fishing regulations, habitat restoration and effective governance are important components of such management. An ecosystem-based and participatory approach can help balance fisheries utilization with long-term conservation of wetland ecosystems and the services they provide

Wetland fisheries and livelihood security

Wetland fisheries play a vital role in supporting the livelihoods and socioeconomic well-being of communities living around inland water bodies. Fish and other aquatic resources provide an important source of food, animal protein, household income and employment, particularly for rural and resource-dependent populations. Fishing activities in wetlands are often closely linked with fish marketing, processing, transportation, net making and other allied occupations, creating additional livelihood opportunities along the fisheries value chain. Seasonal wetlands and floodplain water bodies can provide diverse fish resources that contribute to household nutritional security and help reduce dependence on other income sources. Small-scale fishers often rely on traditional fishing practices and locally available resources, making the ecological condition of wetlands directly relevant to their economic stability. Indian floodplain wetlands have shown that fisheries contribute

substantially to both livelihood and nutritional security among fishing communities (Sarkar *et al*., 2018). However, declining fish stocks, habitat degradation, pollution, restricted access to fishing grounds and changing hydrological conditions can reduce fishing income and increase livelihood vulnerability. Climate variability can further influence fish availability and seasonal fishing opportunities. Sustainable management of wetland fisheries therefore needs to consider both ecological sustainability and the livelihood requirements of local communities. Strengthening community-based management, improving access to markets and technology, developing alternative livelihood opportunities and ensuring equitable access to wetland resources can improve the resilience of wetland-dependent communities. Thus, conserving wetland ecosystems and maintaining productive fisheries are closely connected with long-term livelihood security.

Wetland biodiversity and fisheries resources

Wetlands support rich biological diversity and serve as important habitats for fish, crustaceans, molluscs, aquatic plants, birds and other aquatic and terrestrial organisms. Their high productivity, seasonal flooding and connectivity with rivers and surrounding habitats create favourable conditions for feeding, breeding, spawning and nursery development of many fish species. Wetland fisheries resources include commercially important food fishes as well as small indigenous fish species that contribute to local food and nutritional security. Floodplain wetlands, beels, lakes, marshes and mangrove-associated wetlands can harbour diverse fish assemblages, with species composition varying according to water depth, vegetation, hydrological connectivity, water quality and seasonal conditions. Fish diversity also contributes to ecosystem functioning by supporting food-web interactions and nutrient cycling. In addition to fish, wetland biodiversity provides complementary resources such as aquatic plants, shellfish and other organisms that may support local livelihoods. However, habitat alteration, pollution, excessive fishing pressure, invasive species, fragmentation and changes in natural hydrological regimes can cause declines in species richness and fisheries productivity. Loss of aquatic vegetation and breeding habitats can further reduce recruitment and affect the long-term availability of fish resources. Conservation of wetland biodiversity is therefore essential for maintaining productive and resilient fisheries. Sustainable management should protect critical habitats, maintain natural hydrological connectivity, regulate fishing pressure and conserve native species while allowing responsible use of fisheries resources (Barletta *et al*., 2010).

Major threats to wetland fisheries

Wetland fisheries are increasingly threatened by a combination of ecological, environmental and anthropogenic pressures that affect fish abundance, biodiversity and ecosystem productivity. Habitat degradation and conversion of wetlands for agriculture, urban development, aquaculture and other land-use activities are major causes of declining fisheries resources. Pollution from domestic sewage, agricultural runoff, industrial effluents and plastic waste can deteriorate water quality and adversely affect fish health and survival. Overfishing, destructive fishing practices and excessive harvesting of juvenile and breeding fish can reduce natural fish stocks and disturb population structure. Alteration of natural water flow through dams, embankments, drainage and water abstraction can reduce the connectivity between wetlands and rivers, limiting fish migration and recruitment. The introduction and spread of invasive alien species may further compete with native fishes for food and habitat. Climate change is also emerging as an important pressure through changes in rainfall, temperature, droughts, flooding patterns and water availability (Junk *et al*., 2013). These interacting pressures can reduce fish diversity, modify species composition and

decrease the capacity of wetlands to support fisheries and dependent communities. Weak enforcement of fisheries regulations, inadequate monitoring and limited participation of local stakeholders can further increase resource degradation. Addressing these threats requires coordinated management that combines habitat protection, pollution control, responsible fishing practices, restoration of hydrological connectivity and effective community-based governance.

Table 1. Major threats to wetland fisheries and sustainable management measures

Major threats	Potential impacts on wetland fisheries	Sustainable management measures
Wetland conversion and habitat degradation	Loss of fish habitat, breeding and nursery grounds	Wetland protection and habitat restoration
Pollution and poor water quality	Fish mortality, reduced growth and biodiversity loss	Pollution control and regular water-quality monitoring
Overfishing and destructive fishing	Decline in fish stocks and natural recruitment	Fishing regulations, seasonal closures and appropriate mesh size
Hydrological alteration	Reduced fish migration and recruitment	Restoration of natural water flow and river–wetland connectivity
Invasive alien species	Competition with native fishes and alteration of fish communities	Monitoring and control of invasive species
Climate change	Changes in water availability, fish reproduction and species composition	Climate-resilient and adaptive fisheries management
Weak governance and limited monitoring	Poor implementation of conservation measures and resource degradation	Stronger institutions, monitoring and enforcement
Limited community participation	Low compliance and increased resource-use conflicts	Community-based management and co-management

Sustainable management approaches

Sustainable management of wetland fisheries requires an integrated approach that maintains fish production while conserving wetland ecosystems and their biodiversity. Effective management should begin with regular assessment of fish stocks, habitat conditions, water quality and changes in species composition to support science-based decision-making. Appropriate fishing regulations, including seasonal fishing restrictions, mesh-size regulations, protection of breeding grounds and control of destructive fishing practices, can help maintain fish populations and improve natural recruitment. Restoration of degraded wetlands, aquatic vegetation and natural hydrological connectivity is also important for maintaining feeding, breeding and nursery habitats. Pollution control and proper management of agricultural, domestic and industrial wastes are essential for improving water quality and fisheries productivity. Conservation of native fish species and control of invasive species should form an important part of wetland management programmes. Community-based fisheries management can improve compliance with regulations by involving

local fishers in resource monitoring, conservation and decision-making. Co-management arrangements between fishing communities, government agencies and scientific institutions can combine traditional ecological knowledge with scientific information. Sustainable harvesting should also be supported by improved post-harvest practices, market access and value addition to increase benefits without increasing fishing pressure. Climate-resilient management strategies, including habitat restoration and adaptive fisheries regulations, can further strengthen the capacity of wetlands to withstand environmental changes (Moomaw *et al*., 2018). Such integrated approaches can help balance fisheries production, biodiversity conservation and the long-term livelihood needs of wetland-dependent communities.

Community participation and biodiversity conservation

Community participation is essential for the sustainable management of wetland fisheries because local communities are closely connected with wetland resources and possess valuable knowledge of seasonal changes, fish diversity, fishing grounds and traditional resource-use practices. Involving fishers and other resource-dependent groups in planning, monitoring and conservation activities can improve the effectiveness and acceptance of fisheries management measures. Community-based management can support the protection of breeding and nursery areas, responsible fishing practices, seasonal fishing restrictions and conservation of native fish species. Local participation also encourages greater awareness of the ecological importance of wetlands and promotes collective responsibility for preventing pollution, habitat destruction and destructive fishing practices. Co-management involving fishing communities, government agencies, researchers and local institutions can combine scientific knowledge with traditional ecological knowledge to develop locally appropriate management strategies. Such approaches can also improve transparency, strengthen compliance with fisheries regulations and reduce conflicts over access to wetland resources. Conservation activities such as habitat restoration, protection of aquatic vegetation and maintenance of fish refuges can further benefit both biodiversity and fisheries productivity. Providing alternative or supplementary livelihood opportunities can reduce excessive dependence on wetland resources and encourage long-term conservation. Women and other traditionally underrepresented groups should also be included in decision-making and livelihood programmes associated with wetland fisheries. Thus, community participation should be considered an important component of ecosystem-based wetland management, helping to maintain biodiversity while supporting the livelihood and food-security needs of local communities (Pretty *et al*., 2004).

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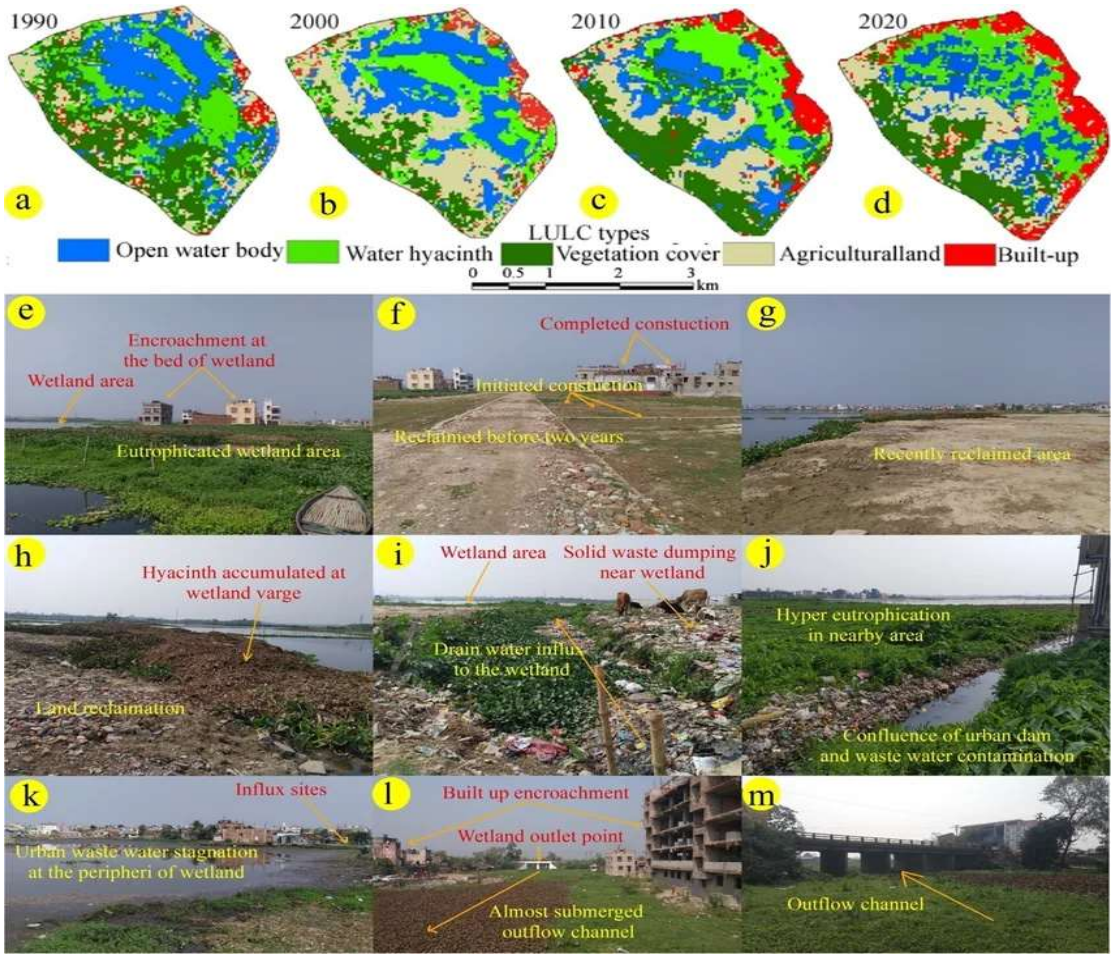


Figure 1. Land-use/land-cover changes and major anthropogenic pressures affecting the wetland ecosystem

Climate change, governance and future priorities

Climate change is becoming an important factor influencing the ecological condition and fisheries productivity of wetland ecosystems. Changes in rainfall patterns, increasing temperatures, prolonged droughts, irregular flooding and extreme weather events can alter water availability, habitat characteristics, fish reproduction and seasonal migration. These changes may interact with existing pressures such as pollution, overfishing, habitat degradation and water abstraction, increasing the vulnerability of wetland fisheries and dependent communities. Effective governance is therefore essential for addressing these combined challenges through coordinated planning, monitoring and enforcement. Management institutions should strengthen wetland protection, fisheries regulations, water-quality monitoring and conservation of critical fish habitats. Greater coordination among fisheries departments, wetland authorities, local governments, research institutions and fishing communities can improve management outcomes. Future priorities should include long-term monitoring of fish diversity and stocks, climate-resilient fisheries management, restoration of degraded wetlands and maintenance of river–wetland connectivity. The use of digital tools, geographic information systems, remote sensing and community-based monitoring can improve assessment and management of changing wetland conditions. Greater attention is also needed to traditional ecological knowledge and locally appropriate adaptation strategies. Policies

should promote sustainable resource use while ensuring equitable access to fisheries resources and livelihood opportunities. Strengthening scientific research, institutional capacity, community participation and adaptive governance will be important for maintaining wetland biodiversity and fisheries under future environmental change (Sarkar *et al*., 2020).

Conclusion

Wetland fisheries are closely linked with biodiversity conservation, food security and the livelihoods of communities that depend on aquatic resources. Healthy wetlands provide important habitats for fish and other aquatic organisms while supporting fisheries production, employment and household income. However, habitat degradation, pollution, overfishing, hydrological alteration, invasive species and climate change are increasingly affecting the sustainability of wetland fisheries. Addressing these challenges requires management approaches that integrate fisheries production with ecosystem conservation and community livelihood needs. Habitat restoration, responsible fishing practices, protection of breeding and nursery areas, pollution control and maintenance of natural hydrological connectivity are essential for sustaining fisheries resources. Active participation of local communities can further strengthen conservation, monitoring and compliance with management measures. Effective governance and collaboration among communities, fisheries managers, researchers and other stakeholders are also necessary for long-term wetland management. Future strategies should focus on climate-resilient management, biodiversity monitoring, restoration of degraded wetlands and sustainable utilization of fisheries resources. An ecosystem-based and participatory approach can help maintain ecological functions while ensuring continued benefits to wetland-dependent communities. Sustainable wetland fisheries management is therefore essential for achieving a balance between livelihood security, fisheries productivity and biodiversity conservation for present and future generations.

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FROM WEED TO WONDER: BISHKHAPRA (*Trianthema portulacastrum*) AS A MEDICINAL AND NUTRITIONAL RESOURCE

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Abstract

Trianthema portulacastrum L. (Horse Purslane or Bishkhapra) is an underutilized medicinal plant with significant nutritional and therapeutic potential. Traditionally used in Ayurveda for treating urinary, digestive, inflammatory, and liver disorders, it is rich in minerals, flavonoids, alkaloids, and phenolic compounds. Scientific studies have reported antioxidant, hepatoprotective, antimicrobial, anti-inflammatory, diuretic, hypoglycemic, and potential anticancer activities. The plant thrives in drought-prone, saline, and degraded soils, making it suitable for climate-resilient agriculture. Despite its value as a functional food and medicinal resource, further research is needed to validate its health benefits and support commercial cultivation and utilization.

Introduction

The shifting perspective on underutilized plants reflects a growing recognition that agricultural biodiversity harbors untapped economic and nutritional value. *Trianthema portulacastrum* L., a succulent annual or perennial herb native to arid and semi-arid regions of Africa and Asia, exemplifies this transition. In India, it has been classified as a seasonal weed in cotton, groundnut and vegetable cultivation, yet it has been used in traditional ayurvedic medicine for centuries to treat inflammatory conditions, urinary disorders and gastrointestinal complaints (Upadhyay *et al*., 2014). Recent phytochemical and ethnobotanical research has reframed the plant as a potential functional food and medicinal agent, warranting systematic cultivation.

The plant's success in marginal environments, thriving in saline, calcareous and drought-prone soils where conventional crops fail, positions it as an adaptation strategy for climate variability and soil degradation. Its high mineral content, alkaloid profile, and reported antioxidant properties align with growing demand for plant-based nutraceuticals.

Botanical Description and Nutritional Composition

Trianthema portulacastrum, commonly known as Horse Purslane or Bishkhapra, belongs to the family Aizoaceae and is distributed across the Indian subcontinent, particularly in arid zones of Rajasthan, Gujarat and Haryana. The plant is drought-tolerant, salt-hardy, and capable of completing its lifecycle in nutrient-poor, degraded soils. Its fleshy, opposite leaves and small pinkish-purple flowers distinguish it from related species (Soni *et al*., 2012).

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The plant's elevated calcium and iron content, particularly relative to spinach, is noteworthy for bioavailability in populations with mineral deficiencies. However, *T. portulacastrum* contains oxalic acid (245–330 mg/100g dry weight), which limits iron bioavailability and restricts its use for individuals prone to kidney stones (Yadav *et al*., 2018).

Table 1 Comparative nutritional composition of *T. portulacastrum* leaves with spinach (fresh weight basis).

Nutrient	*T. portulacastrum* (mg/100g)	Spinach (mg/100g)	Source
Calcium	246	99	Upadhyay *et al*., 2014
Iron	8.5	2.7	Upadhyay *et al*., 2014
Magnesium	154	79	Upadhyay *et al*., 2014
Potassium	456	558	Upadhyay *et al*., 2014
Protein (%)	3.2	2.9	Soni *et al*., 2012

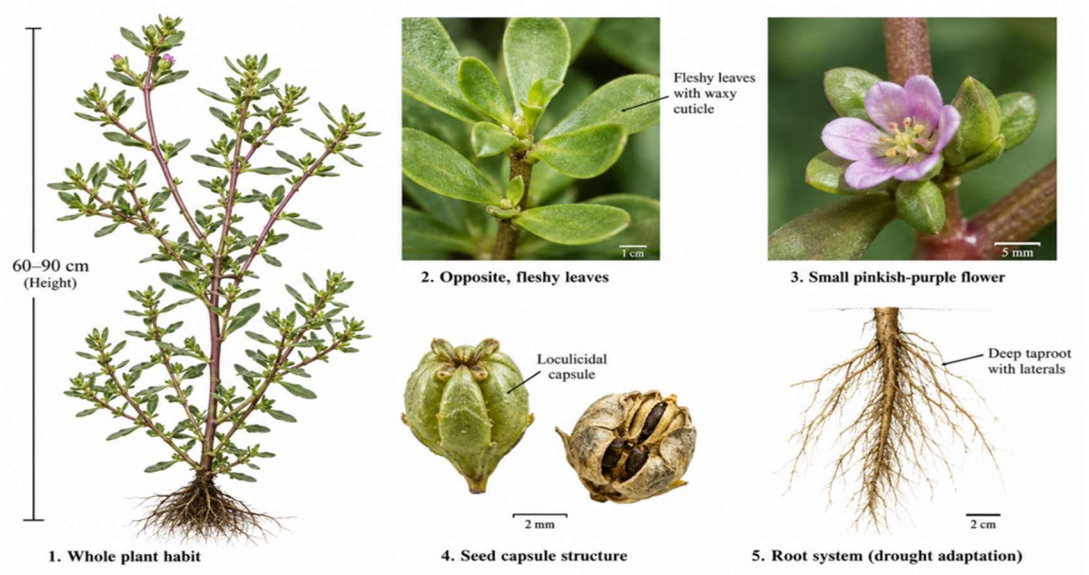


Fig. 1. Plant morphology of Bishkhapra (*Trianthema portulacastrumi).*

Medicinal Properties

Traditionally, different parts of the plant have been used to treat a variety of ailments. The roots are used for asthma, constipation, jaundice, liver disorders, and certain eye diseases, while the leaves are applied for wound healing, edema, ascites, kidney problems, and stomach pain. The whole plant has been employed in the treatment of bronchitis, arthritis, digestive disorders, and heart-related ailments.

Ayurvedic texts cite *Trianthema portulacastrum* (Sanskrit: Biskhapra) for treating pitta disorders, urinary calculi, and inflammatory conditions. It also has antioxidant, diuretic, renal, and Anti-inflammatory effects (Karan *et al*., 2010).

One of its most significant activities is its antioxidant potential. The plant is rich in flavonoids and phenolic compounds that help neutralize harmful free radicals, thereby protecting cells, proteins, and DNA from oxidative damage. It also enhances the activity of antioxidant enzymes such as

superoxide dismutase (SOD) and catalase (CAT), which help reduce the risk of chronic diseases associated with oxidative stress. The plant also exhibits strong hepatoprotective activity. Studies have shown that its extracts protect the liver from damage caused by toxins such as carbon tetrachloride, aflatoxin, and paracetamol. These extracts reduce lipid peroxidation, improve antioxidant defenses, and restore normal liver function, supporting its traditional use against jaundice and other liver disorders (Hasanpuri *et al*., 2025).

In addition, *T. portulacastrum* possesses antimicrobial properties against various bacterial and fungal pathogens. The antifungal compound trianthenol disrupts fungal cell membranes, inhibiting fungal growth. The plant also demonstrates anti-inflammatory, analgesic, diuretic, hypoglycemic, and anticancer activities. Bioactive compounds such as quercetin, β-sitosterol, ferulic acid, and β-carotene contribute to these effects, making the plant a promising source of natural therapeutic agents. Traditional and experimental studies further indicate its anti-inflammatory, analgesic, diuretic, hypoglycemic, and potential anticancer properties (Hasanpuri *et al*., 2025).

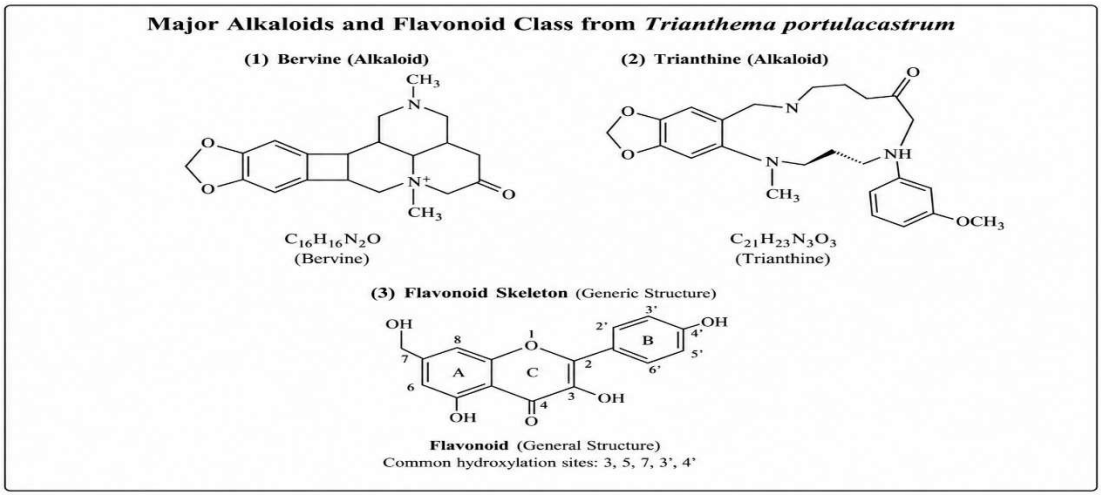


Fig. 2 Phytochemical Profile: Structure diagrams showing major alkaloids (bervine, trianthine) and flavonoid compounds isolated from T. portulacastrum leaves. (Karan et al., 2010)

Cultivation and Practical Applications

Trianthema portulacastrum thrives in temperatures of 15–35°C and completes its lifecycle in 60–90 days, making it suitable for marginal lands unsuitable for conventional crops. It requires minimal water input (200–400 mm annually) and tolerates soil electrical conductivity up to 8 dS/m—levels that severely limit most vegetables (Soni *et al*., 2012). Seed yields of 300–500 kg/ha have been reported, though commercial cultivation protocols remain underdeveloped.

Current applications include: (1) leafy vegetable production for local markets in Rajasthan and Gujarat; (2) inclusion in polyherbal Ayurvedic formulations for urinary and digestive disorders; and (3) exploration as a high-mineral forage crop for livestock in arid regions. No major commercial production chains exist in India, and regulatory status for use in food products or supplements remains ambiguous under India's Food Safety and Standards Authority frameworks.

Conclusion

Trianthema portulacastrum is a remarkable example of how a plant once considered merely a weed can offer significant benefits for both human health and sustainable agriculture. Its ability to grow

under harsh environmental conditions, coupled with its rich nutritional composition and diverse medicinal properties, highlights its potential as a valuable functional food and therapeutic resource. Traditional knowledge and recent scientific studies suggest that the plant possesses antioxidant, hepatoprotective, antimicrobial, anti-inflammatory, and other health-promoting activities. However, to fully realize its potential, further research is needed to validate its medicinal claims, establish safe consumption levels, and develop standardized cultivation and processing practices. With proper scientific support and commercial development, *T. portulacastrum* could become an important crop for improving nutrition, healthcare, and climate-resilient farming systems.

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URBANIZATION AND ITS IMPLICATIONS FOR SUSTAINABLE VEGETABLE PRODUCTION: OPPORTUNITIES FOR URBAN AND PERI-URBAN AGRICULTURE

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Abstract
Urbanization plays a vital role in socio-economic development but poses certain pressures on agricultural land, natural resources, and environment. On the other hand, urbanization can bring new opportunities for urban agriculture, including urban and peri-urban vegetable production. This literature review analyzes the environmental issues associated with urbanization and their impact on agriculture, particularly vegetable production. Major environmental issues of urbanization include land conversion, pollution, soil degradation, rising temperature, and competition for natural resources. In turn, urban and peri-urban agriculture can promote local food production, resource utilization, organic waste recycling, biodiversity conservation, and vegetable availability. Such practices as kitchen gardening, rooftop gardening, composting, rainwater harvesting, and integrated pest management can facilitate vegetable production in urban environments. The review highlights the need to integrate agriculture into urban planning and extension services.

Keywords: Urbanization, Urban agriculture, Peri-urban agriculture, Vegetable production, Food security, Sustainability

Introduction

Urbanization is one of the most significant socio-economic phenomena of the modern world. Increase in population, industrialization, infrastructure development, employment, and service accessibility have facilitated the expansion of urban areas. While cities serve as centers of economic activity and innovations, rapid and haphazard urban growth puts pressure on land, water, energy, and other natural resources.

Urbanization affects agriculture and, in particular, peri-urban agriculture. Fertile agricultural land can be converted to residential, commercial, and infrastructural purposes, reducing the total agricultural land area. Meanwhile, increasing populations in urban areas put pressure on food availability, including vegetables. These trends present certain opportunities for urban agriculture, including kitchen gardens, rooftop gardens, community gardens, institutional gardens, and peri-urban vegetable production.

Urban agriculture can increase the availability of locally produced food, improve the utilization of spaces, and facilitate the recycling of organic resources. However, agricultural production within and around cities may be hampered by pollution, soil degradation, temperature rise, and land and water availability. Therefore, proper planning is needed to ensure sustainable urban agriculture and its positive contribution to food security and environment.

Impact of Urbanization on Agricultural Land Area

One of the negative effects of urbanization is the land conversion to non-agricultural uses. Housing construction, road construction, industries, and commercial infrastructure may encroach on fertile agricultural areas and fragment remaining farms. Such fragmentation reduces production efficiency and decreases the incentives for investments in soil fertility and irrigation.

Nevertheless, peri-urban agriculture has a distinct advantage as the producer lives near the consumer. Shorter distances decrease transportation expenses and post-harvest losses, especially of perishable vegetables. Land use planning needs to protect agricultural land areas and simultaneously allow for proper urban development.

Air and Water Pollution

Urbanization is accompanied by increasing traffic, industrial activity, construction works, and energy consumption. These activities cause an increase in particulate matter and other types of air pollution. Gurjar *et al.* (2010) have analyzed the link between urbanization and air pollution. Vegetables cultivated near major roads and industrial sites may become contaminated by pollutants posing threats to food safety.

Quality of water is another problem. Construction, roads, and paving increase the surface runoff, transporting sediments, pollutants, nutrients, and other contaminants into water bodies. Paul and Meyer (2001) found that urbanization can significantly impact the stream hydrology and water quality. The discharge of industries and untreated sewage can further deteriorate the water quality suitable for irrigation. Thus, water quality monitoring, wastewater treatment, rainwater harvesting, and drainage are essential for safe urban and peri-urban vegetable production.

Soil Degradation and Organic Waste Disposal

Urbanization results in the generation of large amounts of organic waste. Its inappropriate disposal contaminates soils and water, and creates sanitation issues. Nevertheless, segregation and composting can be a way to recycle organic waste. Wilson *et al.,* (2006) emphasized the role of recycling in waste management strategies.

Kitchen waste, vegetable residues, and leaves can be used for composting and further applied as organic fertilizers. It helps to dispose of the waste without sending it to dumpsites while at the same time increasing the organic matter content in the soil and nutrient availability. Only properly segregated and composted organic material should be applied as fertilizer to prevent contamination. Thus, urban agriculture can provide a circular resource-use strategy turning organic waste into a resource.

Urban Heat Island and Vegetable Production

Urban areas typically feature higher temperatures than rural areas because of heat storage by concrete, asphalt, and buildings. Oke (1982) explains the physics of urban heat island effect. Temperature increase causes higher evaporation rates and thus increases water demand while negatively affecting the growth and yield of temperature-sensitive vegetable crops.

Urban agriculture can also serve as an adaptation strategy for urban heat islands. Greenery of the rooftop gardens, kitchen gardens, community gardens, and other green spaces can increase the number of urban green areas and provide localized cooling. Chiesura (2004) stressed the environmental significance of urban green spaces. Thus, integration of food producing greenery into urban landscape is beneficial both environmentally and agriculturally.

Urban and Peri-Urban Opportunities

Urban agriculture creates opportunities to produce vegetables even when the conventional agricultural land area is limited. Kitchen gardens, rooftop gardens, vertical gardens, community gardens, and institutional gardens can improve food availability and nutritional security while contributing to food security. Local production reduces dependence on long-distance supply chains and allows consumers to obtain fresh vegetables.

Sustainable practices, such as composting, mulching, rainwater harvesting, efficient irrigation, crop diversification, and integrated pest management can increase resource-efficiency. They help to decrease environmental pressure and preserve productivity. Urban agriculture can also help to conserve biodiversity when crops, flowering plants, and environment-friendly pest management methods are used.

Extension Education

The implementation of sustainable urban agriculture requires adequate technological knowledge, awareness, institutional support, and communication. The role of agricultural extension personnel is to promote such practices as kitchen gardening, rooftop cultivation, compost making, water conservation, integrated pest management, and safe vegetable production.

Such tools as demonstrations, training courses, social media, mobile advisories, community-based learning, and farmer-scientist interaction can assist in technology dissemination. Collaboration among agricultural universities, Krishi Vigyan Kendras, urban local bodies, self-help groups, farmer associations, and urban households can reinforce urban agriculture initiatives.

Conclusion

Urbanization brings both challenges and opportunities for agriculture. Haphazard urbanization can cause land conversion, pollution, soil degradation, temperature increase, and competition for natural resources potentially affecting vegetable production and local food security. At the same time, urban and peri-urban agriculture can be a means of integrating food production into urban environment.

Kitchen gardens, rooftop gardens, community gardens, and peri-urban vegetable production can increase food availability while recycling organic resources and contributing to environmental sustainability. Composting, rainwater harvesting, efficient irrigation, crop diversification, and integrated pest management can further strengthen these systems. Future urbanization should take into account the significance of agriculture and protect peri-urban agricultural areas. Strengthening the agricultural extension and communication can help urban households and producers to adopt appropriate technologies and environmentally safe practices. A combined effort of farmers, urban households, extension agencies, local governments, and agricultural institutions can turn urbanization from the pressure on agriculture to the opportunity for sustainable local food systems.

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TAMIL NADU'S AQUATIC HERITAGE -*Dawkinsia tambraparniei* – THE TAMIRAPARANI BARB

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An Introduction to the Tamiraparani Barb

Dawkinsia tambraparniei is a medium-sized, slender freshwater fish belonging to the family Cyprinidae. It is an endemic fish species of the Tamiraparani (Tamraparni) river basin in southern India (Johnson *et al*., 2014). This fish was first described by E. G. Silas in 1954. Initially, it was classified under the name *Puntius tambraparniei*. Later, following revisions in the classification of South Asian barb fishes, it was transferred to the genus *Dawkinsia i*n 2012 (Silas, 1954; Pethiyagoda *et al*., 2012). One of its important identifying features is the presence of distinct black markings, particularly near the region before the beginning of the anal fin. These markings help distinguish it from closely related *Dawkinsia* species(Pethiyagoda *et al*., 2012).

Taxonomic Classification :(Pethiyagoda *et al*., 2012).

Taxonomic Rank	Scientific Name
Kingdom	*Animalia*
Phylum	*Chordata*
Class	*Actinopterygii*
Order	*Cypriniformes*
Family	*Cyprinidae*
Subfamily	*Barbinae*
Genus	*Dawkinsia*
Species	*Dawkinsia tambraparniei*

Why is it Called *Dawkinsia tambraparniei?*

The genus name *Dawkinsia* was given in memory of the British evolutionary biologist Richard Dawkins. Dawkins – derived from the name Richard Dawkins.

- ia – a Latin-style suffix commonly used in genus names.
- *tambraparniei* – refers to the natural habitat of this fish, the Tamiraparani River.
- Tambraparni – an old or alternative name for the Tamiraparani River.
- i – a Latin form indicating association or belonging.

Thus, the name *Dawkinsia tambraparniei* reflects both its taxonomic identity and its association with the Tamiraparani River (Pethiyagoda *et al*., 2012).

Body Structure

Dawkinsia tambraparniei is a moderately elongated barb with a slightly laterally compressed body. It can grow up to approximately 12.8 cm standard length (FishBase, 2025).The body colour generally ranges from silver to brass, with distinct black marking (FishBase, 2025) .One of its most important identifying characteristics is the presence of black spots or bands before the beginning of the anal fin(Pethiyagoda *et al*., 2012; FishBase, 2025).

Habitat and Distribution &Natural Environmental Conditions

Dawkinsia tambraparniei is an endemic freshwater fish of the Tamiraparani River and its tributaries.It is associated with the Tamiraparani river basin in the Tirunelveli and Tenkasi districts of Tamil Nadu(Johnson *et al*., 2014; Kannan & Johnson, 2020) .The Tamiraparani River originates in the Agasthyamalai region of the Western Ghats, flows eastwards and finally joins the Gulf of Mannar(Kannan & Johnson, 2020).The flow of the river is significantly influenced by both the Southwest and Northeast monsoons. Therefore, seasonal variations occur in water discharge, current velocity and water turbidity (Kannan & Johnson, 2020).*D. tambraparniei* has been reported from both flowing sections of the river basin and relatively calm water areas(Johnson *et al* ., 2014; Kannan & Johnson, 2020).

1. Temperature 18–25°C
2. pH 6–8
3. water hardness approximately 36–268 ppm
4. Behaviour: Schooling
5. Water zone: Mainly pelagic or middle-water region (FishBase, 2025).

Food and Feeding Habits

Dawkinsia tambraparniei is an omnivorous fish(Fish Base, 2025).Its natural diet includes worms, aquatic insects, small crustaceans, plant materials and organic detritus. In ornamental fish culture, it can accept quality dry feeds such as flakes and small pellets. Live or frozen foods such as bloodworms and brine shrimp can also be provided(ICAR–CIFA, 2014–15).

Sexual Dimorphism

1. Male Fish

During the breeding season, males develop more attractive and bright red and silver colours.Their dorsal fin filaments become elongated. Small tubercle-like structures may also appear around the snout region (FishBase,2025).

2. Female Fish

Females are generally slightly larger than males and have a more rounded or thicker abdomen. Unlike males, females usually do not develop the same bright colours or elongated finfilaments (FishBase, 2025).

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Spawning and Mating Behaviour

During reproduction, the male swims around the female and displays its elongated fin filamentsas part of the mating behaviour. The female scatters eggs among rock crevices or aquatic vegetation such as Hydrilla, while the male releases sperm over the eggs for fertilization. The species does not provide parental care after spawning. Fertilized eggs generally hatch within 24–48 hours, and the young fish gradually become free-swimming(ICAR–CIFA, 2014–15).

Can It Be Cultured as an Ornamental Fish?

The Tamiraparani Barb is a native fish species with potential interest in ornamental fish culture because of its attractive body colour, active swimming behaviour and schooling nature(Johnson et al., 2014).When maintained in an ornamental aquarium, sufficient swimming space, good filtration and well-oxygenated water are important(ICAR–CIFA, 2014–15).

To create an environment similar to its natural habitat, the following conditions can beprovided:

- A sufficiently large aquarium
- Good filtration
- Moderate water flow
- Clean and oxygen-rich water
- Temperature of 18–25°C
- pH of 6–8
- Aquatic plants along the sides of the aquarium
- Open swimming space in the middle (FishBase, 2025).

As this is a peaceful schooling fish, keeping several individuals of the same species together can help display their natural schooling behavior(FishBase, 2025).**(**Since this species has a very restricted natural distribution and faces several threats to its riverine habitat, it has been classified as Endangered (EN) in the IUCN Red List**).**

Captive Breeding in Aquarium

Dawkinsia tambraparniei can be bred in ornamental fish aquariums by following general breeding methods used for barb fishes (ICAR-CIFA, 2014)**,**For breeding, the following facilities can be provided:

- A sufficiently large spawning tank
- Good filtration
- Fine-leaved aquatic plants or a spawning mop
- Gravel or a mesh layer to prevent adults from eating the eggs
- Live or frozen protein-rich feeds for breeding-condition fish(ICAR-CIFA, 2014).

The eggs may attach among aquatic plants. Since adult fish may consume both eggs and young ones, the adults should be separated after spawning. Under suitable temperature conditions, the eggs may hatch within approximately 24–36 hours. After a few days, the fry begin to swim freely During the early stage, infusoria or very fine fry food can be provided. As the fry grow, they can gradually be shifted to foods such as newly hatched brine shrimp (ICAR-CIFA, 2014).

Influence of Tamiraparani River Water – Effects of Pollution

The quality of Tamiraparani River water is very important for the survival of this fish. Activities and changes in the river such as :

1. Agricultural waste
2. Domestic wastewater
3. Water pollution
4. Changes in the natural flow of the river can affect the habitat of aquatic organisms (Kannan & Johnson, 2020).

Let Us Protect It from Extinction – Conservation

Dawkinsia tambraparniei is assessed as Endangered (EN) in the IUCN Red List(IUCN Red List, 2025). Its very restricted natural distribution is an important factor in its conservation. Major Threats to the Tamiraparani River Basin. The important threats include:

1. Excessive water extraction for agriculture and drinking purposes
2. Changes in natural river flow caused by dams and irrigation structures
3. Pollution from agricultural and domestic wastes
4. Changes in the natural seasonal flow pattern of the river
5. Natural habitat degradation
6. Collection of fish for the ornamental fish trade (Johnson et al., 2014; Kannan & Johnson, 2020).

Recent Studies on the Tamiraparani Barb

1. Progress in Captive Breeding

Studies conducted by ICAR–NBFGR reported that *D. tambraparniei* could be bred under captive conditions using a simple method without hormonal treatment. Eggs were observed approximately 24 hours after introducing the fish into the breeding tank. Hatching occurred within 12–15 hours.An average of approximately 220 eggs per female was obtained, with 90% fertilization and 85% hatching reported (ICAR–NBFGR, 2024).

2. Development of Breeding Technology

According to ICAR studies, simple hormone-free breeding and rearing methods have been developed for indigenous ornamental fishes of the Western Ghats. Captive *arulius*.

3. Conservation and Ornamental Fish Culture

This fish has been listed as an endangered species in the ICAR–NBFGR Fish Barcode Information System. Therefore, instead of continuously collecting fish from natural habitats, producing juveniles through captive breeding can be an important approach for both conservation and future ornamental fish culture. Thus, the Tamiraparani Barb is not only an attractive ornamental fish but also an important native fish species of Tamil Nadu with potential for conservation-oriented and sustainable ornamental fish culture(ICAR–NBFGR, 2024).

Market Value and Commercial Opportunity

The Tamiraparani Barb (*Dawkinsia tambraparniei*) also has commercial value in the international ornamental fish market(Johnson et al., 2014).On 19 May 2024, an approximately 6 cm *D. tambraparniei* originating from India was listed at ¥2,980 by Aqua Shop Fin in Japan. Based on the

exchange rate at that time, this was approximately ₹1,594 per fish.However, this was a specific price recorded in the Japanese retail market and should not be considered as the local price in Tamil Nadu(ICAR–NBFGR, 2024).

Conclusion – A Small Treasure of the Tamiraparani

Dawkinsia tambraparniei is not merely an ornamental fish. It represents the unique natural resources of the Tamiraparani River and the freshwater biodiversity of southern India. Its beauty, unique body structure, natural habitat, genetic distinctiveness and potential for ornamental fish culture make it a special native fish species. However, because its natural distribution is limited, protecting the fish alone is not enough. We must also protect the Tamiraparani River, which is its natural home. Protect the Tamiraparani Barb – Protect the Aquatic Heritage of Tamil Nadu.

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FEED THE SOIL TO FEED THE CROP: A SOIL-HEALTH-CENTRED PATHWAY FOR SUSTAINABLE AND CLIMATE-RESILIENT AGRICULTURE IN INDIA

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Abstract
Indian agriculture has achieved remarkable gains in food production, but continued intensification has created new challenges, including depletion of soil organic matter, nutrient imbalance, declining soil biological activity, compaction, micronutrient deficiencies, declining water-use efficiency and increasing vulnerability to drought, heat and erratic rainfall. The traditional approach of primarily "feeding the crop" through external fertilizer inputs is no longer sufficient to sustain productivity over the long term. India needs to move towards a soil-health-centred production paradigm - Feed the Soil to Feed the Crop." This approach recognizes soil as a living ecosystem and emphasizes the continuous supply of organic carbon, nutrients and biological inputs while minimizing soil disturbance and recycling farm-derived biomass. The proposed framework integrates soil-test-based balanced fertilization with farmyard manure, compost, green manure, crop-residue recycling, biofertilizers, biostimulants, crop diversification, legumes, conservation agriculture, efficient irrigation and precision nutrient management. Long-term Indian experiments demonstrate that integrated nutrient management can increase soil organic carbon, microbial activity and nutrient availability, while conservation agriculture can improve aggregation, carbon stocks and system productivity. Meta-analysis of Indian studies has further shown that integrated nutrient management can improve crop yield, soil carbon and microbial biomass compared with exclusive reliance on mineral fertilizers. The paper proposes an India-centric Feed the Soil - Feed the Crop (FSFC) framework based on five principles: build soil organic matter, balance plant nutrients, activate soil biology, protect soil and recycle biomass. Its widespread adoption can contribute simultaneously to food security, climate resilience, resource-use efficiency, farm profitability and sustainable intensification.

Keywords: soil health, soil organic carbon, integrated nutrient management, organic manure, biofertilizers, conservation agriculture, crop residues, balanced fertilization, climate-resilient agriculture, India

Introduction

India's agricultural transformation has been closely associated with improved varieties, irrigation, fertilizers, crop protection and mechanization. These technologies have enabled the country to attain high levels of food production and substantially strengthen food security. However, the productivity gains achieved during the Green Revolution era have also been accompanied in some regions by excessive soil disturbance, intensive monocropping, inadequate return of organic materials, nutrient imbalance and declining soil quality.

The challenge before Indian agriculture is therefore no longer simply to produce more from the soil, but to produce more while continuously regenerating the soil resource. The philosophy of "Feed the Soil to Feed the Crop" provides a simple but scientifically powerful way of expressing this transition.

A crop is fed by nutrients present in the soil solution and soil exchange complex, but the availability of these nutrients depends on soil organic matter, microbial activity, pH, aggregation, moisture, aeration and root activity. Soil organic matter acts simultaneously as a source and reservoir of nutrients, improves aggregation and water retention, supports microorganisms and contributes to the formation of stable soil carbon. Consequently, fertilizer applied to a biologically inactive, structurally degraded soil cannot deliver the same efficiency as fertilizer applied to a healthy and biologically active soil.

Long-term research in India's Indo-Gangetic Plains has demonstrated that combining mineral fertilizers with FYM, crop residues or green manure improves soil organic carbon and its active fractions, microbial biomass and sustainability of rice–wheat systems. The central proposition of this paper is therefore: "Do not merely feed the crop feed the soil that feeds the crop."

This does not imply replacing fertilizers with organic inputs. Rather, it means feeding the soil with carbon, biology and balanced nutrients and feeding the crop according to its actual nutrient requirement.

Why India Needs a Soil-First Agricultural Strategy

Indian soils are extraordinarily diverse, ranging from alluvial soils of the Indo-Gangetic Plains to black soils of central India, red and lateritic soils of peninsular India, hill soils, arid soils and coastal saline soils. Their nutrient-supplying capacity, organic matter content, water-holding capacity and response to fertilizers differ substantially. At the same time, several common problems are emerging.

Declining soil organic matter: Continuous removal of crop biomass without adequate organic-matter replacement reduces the carbon reservoir of cultivated soils. In warm and semi-arid environments, organic matter decomposition can be rapid. Integrated nutrient management involving mineral fertilizers and organic sources improved soil organic carbon, fertility and drought adaptation in rainfed Inceptisols of the Indo-Gangetic Plains.

Nutrient imbalance: India's fertilizer-use pattern has historically become heavily dominated by nitrogen. Imbalances among N, P and K, together with deficiencies of sulphur, zinc, boron, iron and other micronutrients, can reduce nutrient-use efficiency and impair long-term soil fertility. Fertilizer-use imbalance in India is linked partly to policy and price distortions and emphasized its implications for soil health and productivity.

Soil biological degradation: Soil is a biological system containing bacteria, fungi, actinomycetes, archaea, earthworms and other organisms. Excessive disturbance, insufficient organic substrates and inappropriate chemical management can reduce biological activity. Soil microorganisms are essential for decomposition, nutrient mineralization, aggregation and nutrient cycling.

Soil structural degradation: Repeated intensive tillage can disrupt soil aggregates, increase oxidation of organic matter and create compaction layers. Conservation agriculture, by reducing disturbance and retaining residues, can reverse several of these processes.

Long-term research in eastern India found that conservation agriculture increased soil organic carbon concentration and stocks and improved macroaggregation, while maintaining or increasing rice–wheat system productivity.

Increasing climate risks: Drought, heat waves, intense rainfall and prolonged dry periods increasingly affect crop production. A soil rich in organic matter and well-aggregated pores can retain more water, facilitate root growth and buffer short-term climatic stress. Thus, *soil health is an important foundation of climate resilience.*

From "Feed the Crop" to "Feed the Soil to Feed the Crop"

The conventional fertilizer-centric approach focuses primarily on the immediate nutrient requirements of a crop: Crop → nutrient requirement → fertilizer application → yield

The soil-first approach is broader: Soil biological health → organic matter and nutrient cycling → improved soil structure and water availability → efficient root growth → balanced nutrient uptake → healthy crop → sustainable yield. This distinction is critical.

Mineral fertilizers remain indispensable for India's food security because the nutrient quantities required by major crops cannot always be supplied through organic resources alone. However, fertilizer efficiency depends on the condition of the soil into which the nutrients are introduced.

The objective should therefore be *integration rather than substitution*.

A sustainable Indian nutrient-management strategy should combine: soil-test-based fertilizer recommendations; balanced N, P, K, S and micronutrient application; organic manures; crop residues; green manures; legumes; biofertilizers; biostimulants where agronomically justified;

efficient irrigation; appropriate tillage; crop diversification; and precision nutrient management. This is the essence of Integrated Nutrient Management (INM).

Feeding the Soil with Organic Matter

Farmyard manure and compost: Farmyard manure is one of India's oldest soil fertility resources. Properly decomposed FYM supplies nutrients while increasing organic carbon and improving soil physical properties. Composting stabilizes organic materials and reduces the risks associated with fresh biomass application. Where adequate quantities are available, FYM and compost should be incorporated into nutrient-management plans rather than treated as separate "organic farming" inputs.

Vermicompost: Vermicompost can supply nutrients and biologically active organic matter. Its greatest value is often achieved when it is used strategically—for nurseries, vegetable crops, horticultural systems, high-value crops and nutrient-deficient soils—rather than assuming that small quantities can meet the complete nutrient requirement of large cereal crops.

Green manuring: Green manuring provides an effective mechanism for producing biomass directly within the cropping system. Sesbania, sunn hemp and other suitable legumes can contribute nitrogen and organic residues. Green manuring is particularly valuable where livestock manure is scarce. It transforms atmospheric nitrogen and solar energy into biologically derived biomass that can subsequently enrich the soil.

Crop-residue recycling: Crop residues should increasingly be regarded as *soil-building resources rather than agricultural waste*. Rice straw, wheat straw, maize stover, pulses and oilseed residues

contain carbon and substantial quantities of plant nutrients. Burning these residues represents a loss of organic carbon and nutrients and contributes to air pollution. Residue retention under conservation agriculture can improve soil biological and physical properties. Recent Indian research has demonstrated positive effects of residue retention and diversified conservation agriculture systems on soil quality and productivity in the Indo-Gangetic Plains. Residue management should therefore prioritize: retain → shred → incorporate or surface mulch → decompose → recycle nutrients rather than: produce → burn → lose carbon and nutrients.

Feeding the Soil Biology

A healthy soil is not merely a chemical reservoir. It is a living ecosystem.

Biofertilizers: Biofertilizers can improve nutrient availability through biological nitrogen fixation, phosphate solubilization, potassium mobilization and other microbial processes. Important groups include: Rhizobium and related symbiotic nitrogen fixers; Azotobacter; Azospirillum; phosphate-solubilizing microorganisms; potassium-solubilizing microorganisms; and arbuscular mycorrhizal fungi. Their performance depends strongly on crop, soil, climate, microbial strain, application method and environmental conditions. Biofertilizers should therefore complement—not automatically replace—mineral nutrient sources.

Microbial carbon cycling

Organic inputs provide substrates for soil microorganisms. Microbial decomposition converts plant residues into microbial biomass and subsequently into more stable forms of soil organic matter. Thus: Organic residue → microbial activity → microbial biomass → humification and aggregation → improved soil function. The Indian meta-analysis found that integrated nutrient management increased soil carbon and microbial biomass compared with exclusive application of mineral fertilizers, supporting the importance of combining nutrient sources.

Bioenhancers and biostimulants: Biostimulants, seaweed extracts, humic substances and microbial metabolites may support nutrient-use efficiency, root development or stress tolerance under specific conditions. However, their use should be based on demonstrated agronomic benefits rather than replacing established principles of balanced nutrition.

Balanced Plant Nutrition: Feed the Crop Wisely

"Feed the soil" should never become an argument for under-fertilizing crops. The soil-first approach requires balanced and efficient crop nutrition.

Soil-test-based fertilization: Soil testing should form the starting point for nutrient recommendations. Soil Health Cards and digital soil-testing systems can support location-specific recommendations. The objective should be to answer four questions: What nutrients are already available? What nutrients are limiting crop production? How much nutrient does the crop require? How much nutrient can be supplied through soil and organic sources?

Nitrogen management: Nitrogen should be applied according to crop demand and soil supply. Split application, leaf-colour-based approaches, chlorophyll sensors, crop growth monitoring and precision nitrogen tools can improve nitrogen-use efficiency. The objective is not maximum nitrogen application but maximum profitable nitrogen recovery by the crop.

Phosphorus management: Phosphorus should be applied according to soil-test status and crop demand. Excessive phosphorus application can lead to accumulation and economic losses.

Phosphorus management should also consider placement, root-zone availability and interactions with soil pH and organic matter.

Potassium and secondary/micronutrients: Potassium is particularly important for water regulation, disease resistance and stress tolerance. Sulphur, zinc, boron, iron and manganese deficiencies also require greater attention in intensive production systems. Thus, balanced fertilization should evolve from: NPK fertilization to N + P + K + S + micronutrients + organic matter + biological inputs according to soil and crop requirements.

Conservation Agriculture: Protecting What We Feed

Feeding the soil is ineffective if the soil is continuously disturbed and exposed to erosion.

Conservation agriculture is based on three fundamental principles: minimum soil disturbance; permanent soil cover; and crop diversification. These principles complement the FSFC approach. Long-term experiments in eastern India's rice–wheat systems found that conservation agriculture improved soil carbon concentration and stocks and enhanced aggregation, while rice yield remained comparable to or higher than conventional systems. A recent meta-analysis based on Indian studies also showed that conservation agriculture can improve soil carbon sequestration, although yield responses vary by region, crop, soil and duration of adoption. Therefore, conservation agriculture should not be promoted as a rigid package. It should be *adapted to agro-ecological conditions.*

Crop Diversification and Legume Integration

Continuous cereal monocropping can intensify nutrient removal and biological simplification.

Diversification with pulses, oilseeds, millets, fodder crops, vegetables and green-manure crops can improve nutrient cycling and reduce production risks. Legumes are especially valuable because biological nitrogen fixation can contribute nitrogen to the cropping system. Deep-rooted and diversified crops can also explore different soil layers and return different types of residues. A diversified system can therefore be represented as: Cereal + pulse + oilseed + green manure + residue recycling + livestock integration rather than: cereal → cereal → cereal. The 2024 conservation-agriculture research from the western Indo-Gangetic Plains showed that crop diversification and residue retention improved soil quality, productivity and profitability while reducing yield-scaled global warming potential.

Water Management and Soil Health

Water and soil management cannot be separated. Healthy soils improve infiltration and water storage, while appropriate irrigation protects soil biological processes and nutrient uptake.

India should increasingly promote: irrigation scheduling based on crop demand; drip and sprinkler irrigation where appropriate; alternate wetting and drying in suitable rice systems; mulching; rainwater harvesting; conservation of soil moisture; improved drainage in waterlogged areas; and fertigation where technically and economically appropriate. Organic matter plays a central role because improvements in aggregation and pore continuity can increase infiltration while increasing the soil's capacity to retain plant-available water. Increasing soil organic carbon through integrated nutrient management improved soil fertility and helped buffer drought effects in rainfed semiarid systems.

Regional Application of the Feed-the-Soil Approach in India

A national soil-health strategy must recognize India's enormous agro-ecological diversity.

Indo-Gangetic Plains: Priority should be given to: rice–wheat diversification; zero and reduced tillage; residue retention; balanced fertilization; green manuring; micronutrient management; and precision nitrogen management.

Central and Peninsular India: Black and red soils require emphasis on: residue recycling; moisture conservation; balanced NPK; sulphur and micronutrient management; legumes; reduced tillage; and drought-resilient cropping systems.

Eastern India: The eastern region has enormous potential for: rice intensification through improved establishment methods; pulses and oilseeds; conservation agriculture; green manures; residue recycling; and improved drainage and water management.

Arid and Semi-arid India: Priority should be given to: organic-matter conservation; drought-resilient crops; farmyard manure; mulching; rainwater harvesting; legumes; integrated nutrient management; and agroforestry.

Himalayan and hill agriculture*:* Soil erosion control becomes central. Contour farming, vegetative barriers, mulching, cover crops, reduced tillage, agroforestry and organic matter restoration should receive priority.

Livestock–Crop Integration and Circular Nutrient Management

India possesses a major but underutilized opportunity through integration of crops and livestock. Crop residues can feed livestock; livestock manure can return nutrients and carbon to fields. This creates a circular nutrient economy: Crop → residue → livestock → manure → soil → crop. Similarly: Crop residue → compost → soil organic matter → microbial activity → nutrient cycling → crop. Such circular systems can reduce dependence on externally purchased inputs while improving resource-use efficiency. However, organic resources are limited. Therefore, the most efficient use of manure should be determined according to nutrient content, crop requirement and soil-test information rather than applying arbitrary quantities.

Digital and Precision Soil Management

The future of "Feed the Soil to Feed the Crop" should be data-driven. India can combine: Soil Health Card data; GIS-based soil maps; remote sensing; drones; IoT soil-moisture sensors; digital weather information; crop-growth monitoring; variable-rate nutrient application; artificial intelligence; and mobile-based farmer advisories. The next generation of soil management should move from average fertilizer recommendations to field-specific and even management-zone-specific recommendations. A farmer should eventually receive a recommendation such as: "Apply this amount of nitrogen, phosphorus, potassium, sulphur and zinc to this part of the field, retain this quantity of residue, irrigate at this soil-moisture threshold and incorporate this organic resource." Such precision would transform Soil Health Cards from static diagnostic documents into dynamic soil-management tools.

13. A Five-Pillar FSFC Framework for India

The proposed *Feed the Soil–Feed the Crop (FSFC) framework* can be organized into five mutually reinforcing pillars.

Pillar	Major interventions	Expected outcomes
1. Feed soil carbon	FYM, compost, green manure, residues, cover crops	Higher SOC, aggregation and water retention

Pillar	Major interventions	Expected outcomes
2. Feed soil biology	Biofertilizers, microbial inoculants, organic substrates	Higher microbial activity and nutrient cycling
3. Feed crop nutrients	Soil-test-based NPKS + micronutrients	Balanced nutrition and higher NUE
4. Protect soil	Zero/reduced tillage, residue cover, erosion control	Lower erosion and improved structure
5. Recycle resources	Crop–livestock integration, composting, residue recycling	Circular nutrient economy and lower input losses

The five pillars should operate together rather than as independent technologies.

14. Long-Term Evidence from India

The strongest argument for this approach comes from India's long-term field experiments. Long-term integrated nutrient management research in the Indo-Gangetic Plains has shown that combining mineral fertilizers with organic inputs improves soil organic carbon, particulate organic carbon and microbial biomass carbon while supporting sustainable rice–wheat production. Similarly, a 17-year maize–wheat experiment in north-western India demonstrated improvements in soil organic carbon, available nutrients and micronutrient status when FYM was integrated with mineral fertilizers. More recently, 33-year long-term experiments across different Indian soil orders have provided further evidence that integrated organic management can increase soil organic carbon while maintaining yield sustainability These findings collectively reinforce a central principle: Soil fertility is not created in one season; it is built through cumulative management over years and decades.

Policy Priorities for India

To operationalize the FSFC concept, India should move towards a broader soil-health policy architecture.

Make soil organic carbon a central soil-health indicator: Soil testing should move beyond N, P and K to include soil organic carbon; bulk density; pH; electrical conductivity; available micronutrients; microbial indicators where feasible; and soil biological activity.

Promote organic-resource recycling: Policies should support decentralized composting, residue management, biomass recycling and village-level organic-resource centres.

Incentivize residue retention: Farmers should receive economic incentives for beneficial residue management rather than allowing residue burning to remain an economically attractive option.

Strengthen balanced fertilization: Fertilizer policy should progressively encourage nutrient balance and soil-test-based application rather than simply maximizing fertilizer availability.

Promote integrated nutrient management: INM should become a mainstream strategy across irrigated and rainfed agriculture. The objective should be efficient combination of organic, inorganic and biological nutrient sources.

Build Village Soil Health Service Centres: Local service centres could provide: soil testing; compost quality assessment; biofertilizer availability; fertilizer recommendations; residue-management services; precision application; crop advisories; and digital soil records. Such centres would convert soil-health management from a laboratory activity into a practical farm service.

A Farmer-Level Operational Model

The FSFC approach can be translated into a simple annual sequence:

Step 1: Test the soil.
Step 2: Identify nutrient deficiencies and soil constraints.
Step 3: Add available organic resources such as FYM, compost or green manure.
Step 4: Retain and recycle crop residues wherever possible.
Step 5: Apply balanced fertilizers according to soil-test and crop requirements.
Step 6: Use biofertilizers or other biological inputs where crop- and soil-appropriate.
Step 7: Minimize unnecessary tillage.
Step 8: Maintain soil cover.
Step 9: Diversify crops and include legumes.
Step 10: Monitor crop growth, soil moisture and nutrient status.
Step 11: Measure soil organic carbon and other soil-health indicators periodically.
Step 12: Adjust the nutrient and soil-management plan for the next season.

This creates a continuous improvement cycle: Test → Feed → Protect → Grow → Recycle → Measure → Improve

From Sustainable Agriculture to Regenerative Agriculture

The "Feed the Soil to Feed the Crop" philosophy goes beyond conventional sustainability. Sustainable agriculture seeks to maintain productivity without degrading resources. Regenerative agriculture seeks to actively improve soil, biological and ecological functions. Thus, the FSFC framework provides a practical bridge between: Integrated Nutrient Management → Soil Health Management → Conservation Agriculture → Regenerative Agriculture → Climate-Resilient Agriculture**.** This progression is particularly relevant to India because soil restoration can simultaneously improve productivity, water security, climate resilience and farm profitability.

Challenges and Safeguards

The approach should not be romanticized. Organic inputs are limited, variable in quality and costly to transport. Biofertilizers can be inconsistent under unfavourable field conditions. Conservation agriculture can face weed-management and machinery constraints. Crop-residue retention may temporarily immobilize nutrients under certain conditions. Zero tillage is not universally appropriate. Therefore, India needs *evidence-based, location-specific soil management,* not a one-size-fits-all prescription. Importantly, the soil-first philosophy should not mean "organic instead of fertilizer." Nor should it mean "more inputs." The objective is *better soil function with the right combination of inputs at the right rate, right time, right place and right source.*

Future Research Priorities

India should strengthen research in six areas:

1. Soil organic carbon thresholds for different agro-ecological regions.
2. Soil microbiome-based indicators of soil health.
3. Long-term effects of biofertilizers and bio stimulants under farmer conditions.
4. Carbon and nutrient dynamics under residue recycling.
5. Economic valuation of soil-health improvements.
6. Digital soil-health decision-support systems integrating soil, weather, crop and remote-sensing information.

Research should increasingly evaluate complete cropping systems rather than individual inputs.

Conclusion

India's next agricultural transformation must begin beneath our feet. The future of Indian agriculture cannot depend exclusively on supplying more external nutrients to crops. It must depend on building soils capable of supplying, storing, cycling and efficiently delivering nutrients to crops. The principle “Feed the Soil to Feed the Crop” provides a simple framework for this transformation. Feeding the soil means returning organic matter, recycling crop residues, using green manures, supporting beneficial microorganisms, maintaining soil cover, minimizing disturbance and building soil organic carbon. Feeding the crop means applying balanced NPK, sulphur and micronutrients according to soil-test results and crop demand. Protecting the soil means conservation agriculture, erosion control, efficient water management and crop diversification. Indian evidence from long-term experiments and meta-analyses demonstrates that integrated nutrient management and conservation agriculture can improve soil carbon, biological activity, aggregation, nutrient availability and system productivity. The strategic message for Indian agriculture is therefore clear: Healthy soil → healthy roots → efficient nutrient use → healthy crops → higher and more stable yields → resilient farmers → sustainable agriculture. India should therefore move from a “feed the crop” paradigm to a “feed, protect and regenerate the soil to feed the crop” paradigm. This transition can become one of the foundations of climate-smart, resource-efficient and regenerative agriculture for a food-secure and sustainable India.

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AQUATIC BIODIVERSITY CONSERVATION FOR SUSTAINABLE FISHERIES AND AQUACULTURE

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Introduction

Aquatic biodiversity encompasses the diversity of genes, species and ecosystems occurring in freshwater, brackishwater and marine environments and provides the ecological foundation for sustainable fisheries and aquaculture. Rivers, lakes, reservoirs, wetlands, estuaries, mangroves, seagrass beds, coral reefs and coastal waters support spawning, feeding, nursery and migration of aquatic organisms. These ecosystems also provide essential services such as nutrient cycling, water regulation, carbon storage and food production. The global importance of aquatic biodiversity is reflected in the growing contribution of fisheries and aquaculture to food security and livelihoods. According to FAO, global fisheries and aquaculture production reached about 195 million tonnes of aquatic animals in 2024, with aquaculture contributing approximately 53% of total aquatic animal production. Inland fisheries also produced about 12.3 million tonnes of aquatic animals in 2024, highlighting the importance of freshwater ecosystems (FAO,2026). Fisheries productivity depends strongly on habitat quality, food-web interactions and genetic diversity, while aquaculture relies on healthy ecosystems and aquatic genetic resources. However, overfishing, habitat degradation, pollution, climate change, invasive species and altered hydrological regimes are increasingly threatening aquatic biodiversity. These pressures can reduce species abundance, disrupt ecological interactions and weaken ecosystem resilience. Therefore, biodiversity conservation needs to be integrated into fisheries management and responsible aquaculture development. Maintaining diverse and healthy aquatic ecosystems is essential for sustaining aquatic food production, ecosystem services, livelihoods and long-term aquatic food security.

Importance of aquatic biodiversity for fisheries and aquaculture

Aquatic biodiversity supports fisheries and aquaculture through ecological processes, genetic resources and ecosystem services. Diverse aquatic communities maintain food-web interactions, nutrient cycling, primary production and natural population regulation. Fish and other aquatic organisms require suitable habitats for spawning, feeding, growth and reproduction, making wetlands, floodplains, estuaries, mangroves, seagrass beds, coral reefs and riverine habitats particularly important for fisheries production. Genetic diversity is also valuable for aquaculture because it provides the biological basis for selective breeding, adaptation to environmental change and resistance to diseases. Maintaining genetic variation within cultured populations can improve their capacity to respond to changing environmental conditions and production challenges. Biodiversity also contributes to ecosystem resilience because diverse communities can maintain ecological functions under environmental disturbances. Wetland ecosystems are especially important because they provide productive habitats for fish and other aquatic organisms while supporting local livelihoods and food security (Temple *et al*., 2022). In India, wetlands support fisheries and aquaculture activities but are increasingly affected by habitat modification, pollution

and unsustainable resource use. Therefore, biodiversity conservation is not simply a strategy for protecting rare species; it is also a practical requirement for maintaining productive ecosystems that support sustainable fisheries and aquaculture.

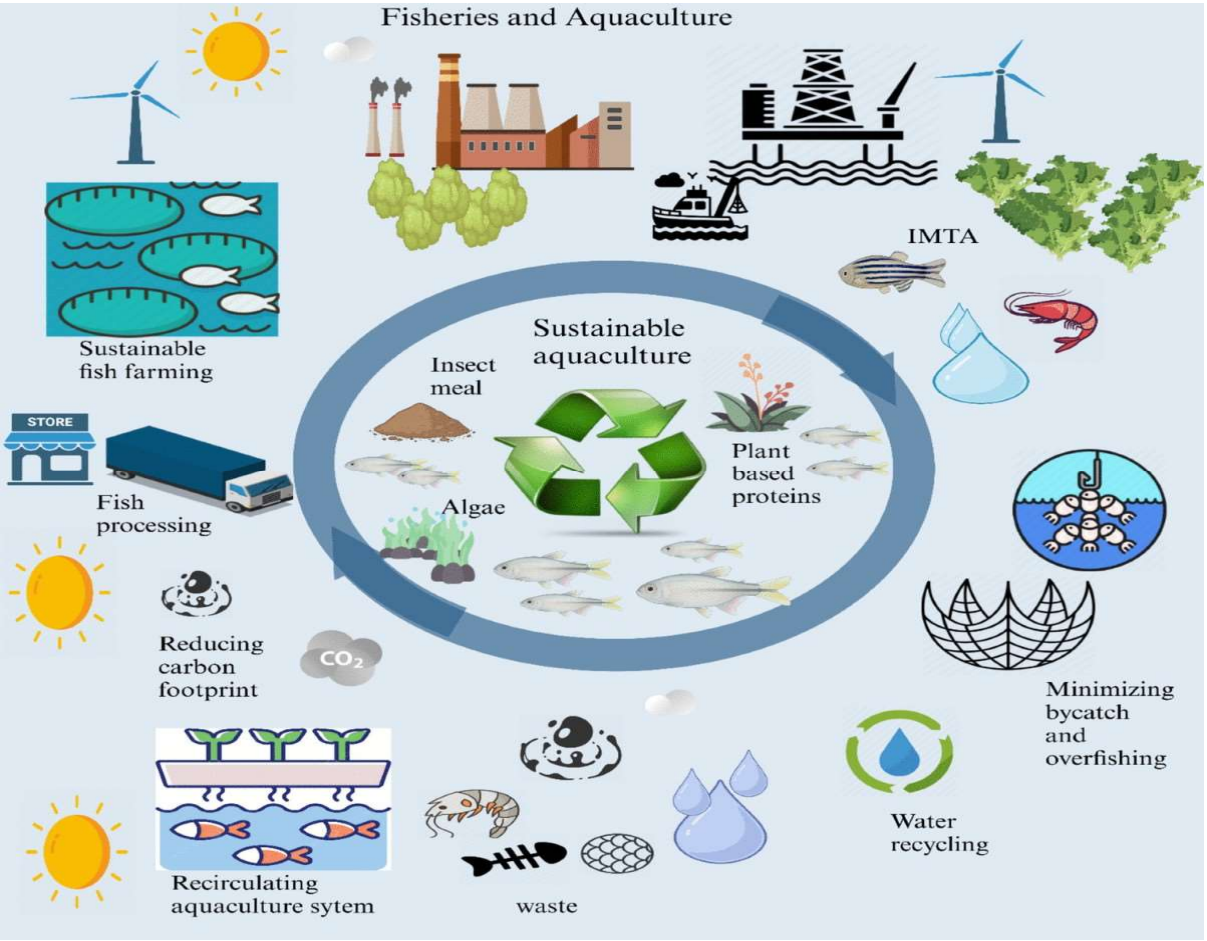


Figure 1. Importance of aquatic biodiversity for fisheries and aquaculture

Major threats to aquatic biodiversity

Aquatic biodiversity is affected by several interacting environmental and anthropogenic pressures. Overfishing can reduce the abundance of target species and alter population structures, while destructive fishing practices may damage habitats and increase the capture of juveniles and non-target organisms. Habitat loss and degradation are major concerns because the conversion of wetlands, mangroves, estuaries, floodplains and other aquatic habitats can remove important spawning and nursery grounds. Pollution from domestic wastewater, agricultural runoff, industrial effluents, plastics, pesticides, pharmaceuticals and other contaminants can adversely affect water quality and aquatic organisms. Climate change adds further pressure through increasing temperature, changes in rainfall and river flow, ocean warming, acidification, sea-level rise and extreme weather events. Dams and other river infrastructure can fragment habitats, alter natural flow regimes and restrict fish migration. Invasive and non-native species may compete with native organisms, transmit diseases and alter food-web relationships. These pressures often occur simultaneously; for example, habitat degradation and pollution can reduce the ability of fish populations to withstand climate-related environmental changes. Recent assessments of Indian freshwater biodiversity have highlighted habitat degradation, altered hydrology and invasive species

as important conservation concerns. Effective biodiversity conservation therefore requires an integrated approach that addresses multiple pressures rather than focusing on a single threat (Petrossian *et al*., 2015).

Conservation strategies for sustainable fisheries and aquaculture

Habitat protection and restoration

Protection of existing aquatic habitats is one of the most important approaches to biodiversity conservation. Healthy rivers, lakes, wetlands, floodplains, mangroves, estuaries and coastal habitats provide spawning, nursery, feeding and refuge areas for fish and other aquatic organisms. Conservation measures should therefore focus on preventing unnecessary habitat conversion, maintaining ecological connectivity and protecting areas of high biodiversity value. Where habitats have already been degraded, restoration may involve wetland rehabilitation, mangrove planting, riparian vegetation recovery, improvement of water quality, restoration of environmental flows and removal or modification of barriers to fish movement. Environmental flows are particularly important in rivers because natural patterns of water quantity and timing influence fish migration, reproduction and habitat availability. Restoration programmes should be based on local ecological conditions and supported by long-term monitoring to determine whether biodiversity and ecosystem functions are recovering. Protection and restoration of aquatic habitats can simultaneously improve biodiversity conservation and fisheries productivity and should therefore be incorporated into fisheries and aquaculture development planning.

Sustainable fisheries management

Sustainable fisheries management is essential for maintaining biodiversity because fishing directly influences aquatic populations and food-web structure. Management measures may include scientifically determined catch limits, minimum size restrictions, seasonal closures, gear regulations, protection of spawning grounds and nursery habitats, bycatch reduction and restrictions on the harvest of threatened species. The ecosystem approach to fisheries considers not only target stocks but also habitats, non-target organisms, food-web interactions and human activities. FAO promotes an ecosystem approach that integrates ecological, social and economic considerations into fisheries management. Area-based management and fish sanctuaries can provide additional protection for important habitats and breeding populations when they are appropriately designed and effectively enforced. Sustainable fisheries management should also incorporate local ecological knowledge and involve fishing communities in decision-making and monitoring. Such approaches can improve compliance with regulations while strengthening community responsibility for aquatic resources. Maintaining sustainable fishing pressure is therefore essential for conserving biodiversity while continuing to provide food and livelihoods (Simataa *et al*., 2025).

Biodiversity-friendly aquaculture practices

Aquaculture can contribute significantly to aquatic food security, but its expansion should be environmentally responsible. Poorly managed aquaculture may contribute to nutrient enrichment, organic loading, disease transmission, chemical pollution, habitat modification and escape of cultured organisms. Sustainable aquaculture practices should therefore include appropriate site selection, efficient feed utilization, suitable stocking densities, water-quality management, waste treatment, biosecurity and prevention of escape. The ecosystem approach to aquaculture emphasizes integrating aquaculture within the wider ecosystem while considering environmental, social and economic objectives. Integrated production systems such as integrated multitrophic

aquaculture, aquaponics and rice–fish culture can improve resource utilization by recycling nutrients between different production components. Recirculating aquaculture systems and other water-efficient technologies can also reduce water use and effluent discharge when properly designed and managed. Genetic management is equally important because uncontrolled release of cultured or non-native organisms may affect wild populations. Therefore, responsible species selection, broodstock management, containment measures and environmental monitoring should form part of biodiversity-friendly aquaculture.

Conservation of threatened species and genetic resources

Conservation of threatened aquatic species requires protection of natural populations and their habitats together with carefully planned species-specific interventions. Habitat restoration, fishing restrictions, protection of breeding areas and restoration of migration routes can help recover declining populations. Conservation hatcheries, captive breeding and restocking may provide additional support when natural populations have been severely reduced, but these measures should be based on scientific assessment. Inappropriate stocking can create genetic, ecological or disease-related risks, particularly when non-native or genetically unsuitable stocks are released. Maintaining genetic diversity is therefore important both for wild populations and cultured stocks. Genetic characterization can help identify suitable broodstock and reduce inbreeding and loss of genetic variation. Conservation aquaculture can contribute to species recovery and stock enhancement, but it should complement rather than replace habitat protection and sustainable fisheries management (Lim *et al*., 2025). A precautionary approach is particularly important when conservation interventions involve movement or release of aquatic organisms.

Pollution control and water-quality management

Good water quality is fundamental to aquatic biodiversity, fisheries and aquaculture production. Excess nutrients, organic matter, pesticides, heavy metals, plastics and other pollutants can affect aquatic organisms directly and alter ecosystem processes. Nutrient enrichment can cause eutrophication and reduce dissolved oxygen, while toxic substances may affect growth, reproduction and survival. Pollution control should therefore focus primarily on preventing contaminants from entering aquatic ecosystems. Agricultural nutrient management, wastewater treatment, reduction of plastic waste, responsible chemical use and improved aquaculture waste management can reduce pollution pressure. In aquaculture, efficient feeding and appropriate stocking densities can minimize uneaten feed and fecal waste. Biofilters, constructed wetlands, recirculating systems and integrated production approaches can further improve nutrient management. Regular monitoring of temperature, dissolved oxygen, pH, ammonia, nutrients and other relevant parameters can provide early warning of environmental deterioration. Maintaining water quality not only protects biodiversity but also improves the productivity and stability of aquaculture systems.

Climate change adaptation

Climate change is becoming an important factor influencing aquatic biodiversity and fisheries production. Changes in water temperature, rainfall, river discharge, ocean warming, acidification, sea-level rise and extreme events can alter species distribution, reproduction, migration and habitat suitability. These impacts may be intensified when aquatic ecosystems are already affected by overfishing, pollution or habitat degradation. Conservation strategies should therefore increase ecosystem resilience by protecting diverse habitats, maintaining ecological connectivity and

conserving genetic diversity. Restoration of wetlands, mangroves, riparian vegetation and other natural habitats can provide additional protection against environmental disturbances. Fisheries management should consider environmental variability when setting harvest levels and management measures. Aquaculture systems can improve resilience through appropriate species and strain selection, improved water management, diversified production systems and early-warning mechanisms. Reducing non-climatic pressures is also important because healthier ecosystems generally have greater capacity to withstand environmental change.

Invasive species management

Invasive species can threaten native aquatic biodiversity by competing for food and habitat, predating on native organisms, transmitting pathogens and altering ecosystem processes. Aquaculture, fisheries enhancement and live-fish transportation can contribute to the movement of non-native species when appropriate safeguards are not implemented. Prevention is generally more effective than controlling established invasive populations. Risk assessment should therefore precede the introduction of new species or strains for aquaculture and fisheries purposes. Quarantine, health screening, secure transportation, escape prevention and responsible disposal of unwanted organisms are important biosecurity measures. Native species should be prioritized where appropriate, particularly in conservation and stock-enhancement programmes. Early detection and rapid response can help prevent newly introduced populations from becoming established. Stronger regulation and monitoring of non-native aquatic species are particularly important in freshwater ecosystems where endemic species may have restricted distributions.

Protected areas and community participation

Protected and conserved aquatic areas can provide spatial protection for important habitats, breeding populations and threatened species. Marine protected areas, fish sanctuaries, wetland conservation areas and freshwater reserves can restrict activities that negatively affect biodiversity and allow populations to recover. Their success depends on appropriate site selection, clearly defined objectives, effective enforcement and long-term monitoring. Community participation is equally important because local fishers and resource users possess valuable knowledge about aquatic ecosystems and seasonal changes. Co-management approaches can involve communities in conservation planning, monitoring, habitat restoration and implementation of fisheries regulations. FAO recognizes participatory approaches as an important component of sustainable small-scale and inland fisheries management. Community-based conservation can include local fish sanctuaries, seasonal fishing agreements, participatory monitoring and awareness programmes. In aquaculture areas, farmers can contribute by reducing effluent discharge, preventing escapes and maintaining water quality. Combining scientific knowledge with local experience can strengthen conservation outcomes and improve acceptance of management measures.

Monitoring, research and digital technologies

Effective conservation requires reliable information on species distribution, population trends, habitat condition and environmental pressures. Conventional field surveys remain essential, but new technologies are providing additional opportunities for biodiversity monitoring. Remote sensing and geographic information systems can support mapping of wetlands, coastal habitats and changes in land and water use. Environmental DNA can help detect aquatic organisms from genetic material present in water and may be particularly useful for rare or difficult-to-observe species. Automated sensors can provide continuous information on water temperature, dissolved oxygen,

pH and other environmental variables, while artificial intelligence and machine-learning approaches can assist in analysing large datasets. Digital monitoring can improve the detection of biodiversity changes and support timely management decisions. However, technological tools should complement rather than replace field surveys and ecological expertise. Standardized sampling, long-term monitoring, data sharing and collaboration among research institutions and management agencies are necessary to convert monitoring information into effective conservation action. Improved biodiversity databases can also support fisheries stock assessment and aquaculture environmental planning.

Emerging approaches and future perspectives

Future aquatic biodiversity conservation will increasingly require integration of ecological science, digital technologies, sustainable production and participatory governance. Advances in environmental DNA, satellite remote sensing, automated sensors, artificial intelligence and spatial modelling can improve the detection and assessment of biodiversity changes. Nature-based solutions, habitat restoration and conservation aquaculture may provide additional opportunities to recover degraded ecosystems and support threatened species when carefully planned and monitored. Sustainable aquaculture is also likely to depend increasingly on resource-efficient systems, improved feed utilization, nutrient recycling, water conservation and stronger biosecurity. Fisheries management will need to become more ecosystem-based and adaptive so that management measures can respond to environmental variability and climate change. At the same time, community participation should remain central to conservation because local stakeholders are directly connected with aquatic resources. Future policies should integrate biodiversity conservation into fisheries, aquaculture, water-resource management, climate adaptation and coastal development rather than treating these sectors independently. The development of clear biodiversity indicators linked with fisheries production, ecosystem health and aquaculture performance will help managers evaluate whether conservation measures are achieving both ecological and socio-economic (Lim *et al*., 2025).

Conclusion

Aquatic biodiversity is fundamental to sustainable fisheries and aquaculture because it supports fish populations, genetic resources, habitats, ecosystem functions and aquatic food production. However, overfishing, habitat degradation, pollution, climate change, invasive species and unsustainable development continue to threaten aquatic ecosystems. Effective conservation requires an integrated combination of habitat protection and restoration, sustainable fisheries management, responsible aquaculture, threatened-species conservation, pollution control, climate adaptation, invasive-species management and protection of important aquatic areas. Scientific monitoring, digital technologies and improved ecological information can strengthen decision-making, while community participation and co-management can improve implementation at the local level. Sustainable fisheries and aquaculture should therefore be developed within the ecological limits of aquatic ecosystems. Integrating biodiversity conservation with aquatic food production can help maintain ecosystem resilience, protect aquatic resources and support the long-term food and livelihood benefits provided by fisheries and aquaculture.

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WATER POLLUTION AND ITS IMPACTS ON FISHERIES RESOURCES AND AQUACULTURE

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Introduction

Aquaculture now contributes nearly half of the fish consumed directly by humans and approximately 43% of the global seafood supply, while fish provide about 20% of the average daily intake of animal protein for around 3.2 billion people worldwide. The rapid expansion and intensification of aquaculture, however, have increased concerns regarding its potential impacts on aquatic environments. Effluents containing uneaten feed, faecal matter, nutrients and other waste products can enter surrounding water bodies, resulting in deterioration of water quality and sediment conditions and potentially affecting farm productivity. The environmental impacts of aquaculture have been assessed using the Aquaculture Eco-Environment and Health Impact model, which considers pollutant emissions, biodiversity loss, invasive alien species and disease transmission, including the spread of antimicrobial resistance. The reported global average impact score of 62.3 indicates considerable environmental pressure, with regional scores of 68.7 in Asia, 58.9 in Africa, 55.6 in Latin America and the Caribbean, 52.4 in North America, 45.2 in Europe and 41.8 in Oceania (Ward *et al*., 2021). Pollutant emissions account for approximately 35% of the overall impact score and represent a major contributor to environmental degradation. In addition, antibiotics, heavy metals and excess nutrients may accumulate in aquatic environments and undergo trophic transfer, creating interconnected ecological risks and potentially affecting ecosystem health and food safety.

Sources of Aquaculture Water Pollution

Excess feed and metabolic waste

Uneaten feed and metabolic wastes are important sources of nutrient and organic pollution in aquaculture systems. Unconsumed feed settles on the pond or seabed and undergoes decomposition, releasing nitrogen and phosphorus into the surrounding environment. Fish also contribute to the organic load through dissolved metabolic wastes, particularly ammonia excreted through the gills, and solid faecal matter. In cage-based systems, these wastes are discharged directly into the underlying sediments, where they can accumulate over time. Excessive accumulation may increase organic matter, nutrient concentrations and oxygen demand, leading to deterioration of sediment and water quality (Carroll *et al*., 2003). Therefore, efficient feed management, appropriate stocking densities and regular monitoring of sediment and water quality are essential for minimizing nutrient accumulation and maintaining sustainable aquaculture production.

Chemical inputs and heavy metals

Various chemical substances, including antibiotics, disinfectants, antifouling agents and feed additives, are used in aquaculture for disease control and farm management. Their inappropriate or

excessive use can introduce chemical residues into surrounding aquatic environments. Heavy metals such as mercury, lead and cadmium are of particular concern because they are persistent and can accumulate in sediments and aquatic organisms. These contaminants may enter aquaculture systems through polluted water, contaminated feed ingredients and farm equipment and can subsequently move through aquatic food webs. Long-term exposure may adversely affect fish health, ecosystem functioning and food safety. Management approaches such as responsible chemical use, improved wastewater treatment, adsorption, biosorption and phytoremediation can help reduce heavy-metal contamination.

Plastics and microplastics

Plastic materials are extensively used in aquaculture, including nets, ropes, cages, tanks, pipes and flotation devices. Their degradation and improper disposal can contribute to the accumulation of plastic debris and microplastics in aquatic environments. Microplastics may enter aquaculture systems through contaminated water, feed ingredients and deteriorating farm equipment. Their ingestion by aquatic organisms can cause physical and physiological stress, including reduced feeding and growth, oxidative stress, impaired reproduction and, at high exposure levels, increased mortality. Microplastics can also carry or release other chemical contaminants, potentially increasing their ecological effects (Padervand *et al*., 2020). Reducing single-use plastics, maintaining farm equipment, improving waste collection and recycling, and using durable alternative materials can help control plastic pollution from aquaculture activities.

Antibiotic resistance and environmental risks

The use of antimicrobial agents in aquaculture can contribute to the development and dissemination of antimicrobial resistance in aquatic environments. Antibiotic residues and resistant microorganisms may enter surrounding water and sediments through farm effluents and organic wastes. Aquaculture environments can therefore act as reservoirs where antibiotic-resistant bacteria and resistance genes persist and potentially spread through aquatic microbial communities. Environmental conditions such as temperature, salinity and pH may influence the persistence and transfer of resistance determinants. Responsible antimicrobial use, disease prevention, vaccination where appropriate, improved biosecurity and effective effluent management are important measures for reducing the environmental spread of antimicrobial resistance.

Table 1. Major pollution sources, primary pollutants, farm-level mitigation measures and monitoring methods in aquaculture

Pollution Source	Primary pollutants	Farm-level Mitigation	Monitoring method
Excess feed and feces	Nitrogen, phosphorus, organic matter	Feed management, settling basins, sediment removal	Water column nutrient testing, sediment organic matter analysis
Chemical inputs and heavy metals	Copper, zinc, cadmium, mercury, organotins	Reduced chemical use, alternative antifouling, phytoremediation	Sediment heavy metal analysis, water column metal testing
Plastics and microplastics	Microplastic particles, phthalates,	Equipment maintenance, recycling,	Visual inspection, litter surveys, water column sampling

Pollution Source	Primary pollutants	Farm-level Mitigation	Monitoring method
	organophosphate esters	biodegradable materials	
Antibiotic resistance genes	Resistance genes, resistant bacteria	Reduced antibiotic use, biosecurity, water treatment	Resistance gene monitoring, water quality testing

Impacts of water pollution on fisheries resources

Changes in fish growth, reproduction and survival

Water pollution can adversely affect fish growth, reproduction and survival by altering the physical and chemical conditions of aquatic environments. Pollutants such as excess nutrients, heavy metals, pesticides, hydrocarbons and other toxic substances can cause physiological stress and impair normal metabolic functions. Prolonged exposure may reduce feeding activity, growth performance and reproductive capacity and can increase susceptibility to disease. Severe deterioration of water quality, particularly low dissolved oxygen and high concentrations of toxic substances such as ammonia, may result in increased mortality of fish and other aquatic organisms (Adeyemo *et al*., 2003).

Fish distribution, abundance and productivity

Changes in water quality can influence the distribution, abundance and productivity of fish populations. Pollution may make certain habitats unsuitable for sensitive species, resulting in changes in species composition and local distribution. Nutrient enrichment can initially increase primary productivity; however, excessive nutrient loading may lead to eutrophication, algal blooms and dissolved oxygen depletion. These conditions can reduce the availability of suitable habitats and food resources and may ultimately decrease fish abundance and fisheries productivity.

Habitat degradation and biodiversity loss

Water pollution can contribute to the degradation of important aquatic habitats, including rivers, lakes, wetlands, estuaries, mangroves and coastal ecosystems. Excess nutrients, organic matter, toxic chemicals and suspended pollutants can alter water quality, sediment characteristics and ecological processes. Habitat degradation can reduce spawning, nursery and feeding areas and negatively affect sensitive aquatic organisms. Persistent pollution may therefore contribute to changes in species composition, reduced biodiversity and disruption of aquatic food webs.

Bioaccumulation and biomagnification of pollutants

Certain pollutants, particularly heavy metals and persistent organic contaminants, can accumulate in aquatic organisms when their uptake exceeds their ability to eliminate them. This process, known as bioaccumulation, can result in increasing concentrations of contaminants within individual organisms. Through biomagnification, pollutant concentrations may further increase at higher trophic levels as contaminated organisms are consumed by predators. Fish and other aquatic organisms can therefore serve as pathways for the transfer of contaminants through aquatic food webs, creating ecological and food-safety concerns.

Fisheries production, food safety and human health

Water pollution can reduce fisheries production by affecting fish survival, growth, reproduction, habitat quality and population abundance. Contaminated aquatic organisms may also accumulate heavy metals, chemical residues, pathogens and other harmful substances, potentially reducing the

quality and market value of fishery products. Consumption of contaminated fish and shellfish may expose humans to harmful substances, particularly when pollutants accumulate at elevated concentrations. Maintaining good water quality, controlling pollutant discharge and monitoring contaminants in aquatic organisms are therefore important for protecting fisheries production, food safety and human health.

Ecological impacts of aquaculture pollution

Sediment degradation

Sediments act as important sinks for organic matter, nutrients and other pollutants released from aquaculture activities. Continuous deposition of uneaten feed and faecal matter increases organic loading and oxygen consumption during decomposition, which may create hypoxic or anoxic conditions in bottom sediments. Such conditions can negatively affect benthic organisms and disturb natural nutrient cycling. Accumulation of nitrogen, phosphorus, heavy metals and other contaminants may further deteriorate sediment quality and increase ecological risks. In pond and cage-based systems, regular monitoring of bottom sediments and appropriate removal or treatment of excessive organic matter are therefore important for maintaining suitable environmental conditions and reducing the long-term accumulation of pollutants.

Nutrient overloading and eutrophication

Excessive discharge of nitrogen and phosphorus from aquaculture can contribute to nutrient enrichment and eutrophication of receiving water bodies. Increased nutrient availability promotes excessive growth of algae and aquatic plants, which can alter ecosystem structure and reduce water quality. Decomposition of accumulated organic matter and algal biomass increases oxygen consumption and may result in dissolved oxygen depletion, particularly during periods of low water circulation. Severe oxygen depletion can cause stress and mortality of fish and other aquatic organisms. Improved feeding practices, efficient nutrient utilization, appropriate stocking densities and effective treatment of farm effluents can help reduce nutrient loading and minimize eutrophication risks.

Habitat degradation and biodiversity loss

Aquaculture activities can affect aquatic habitats when poorly planned or intensively managed. Construction of ponds and coastal farms may lead to the conversion or degradation of sensitive habitats, while organic deposition beneath cages can modify benthic communities and sediment characteristics. Escapes of cultured or non-native species may also create ecological concerns by increasing competition with native species, altering food-web interactions and potentially introducing diseases. Protection of sensitive habitats, responsible site selection, control of farm escapes and environmentally appropriate production practices are important for minimizing biodiversity loss associated with aquaculture.

Microplastic toxicity

Microplastics are increasingly recognized as emerging pollutants in aquaculture environments. They can enter culture systems through contaminated water, feed materials and the degradation of plastic-based equipment and infrastructure. Ingestion of microplastics by aquatic organisms may interfere with feeding, growth, reproduction and physiological functions and can induce oxidative stress and other cellular responses. Microplastics may also adsorb or transport other contaminants, potentially increasing their biological effects. Their presence in cultured fish and shellfish has raised additional concerns regarding food safety and human exposure. Reducing plastic use, improving

equipment maintenance, preventing littering and strengthening collection and recycling practices can help minimize microplastic contamination.

Practical mitigation strategies

Feed management

Efficient feed management is one of the most important approaches for reducing nutrient pollution from aquaculture. Uneaten feed represents both an economic loss and a major source of organic nitrogen and phosphorus entering the culture environment. Feeding rates should therefore be adjusted according to biomass, species, life stage, water temperature and observed feeding activity. Feeding trays, demand feeders and automated feeding systems can improve feeding precision and reduce unnecessary feed losses. Regular monitoring of growth and feed conversion also helps optimize feed utilization and minimize environmental loading (Zhang *et al*., 2025).

Biofiltration

Biofiltration uses microorganisms and other biological processes to remove or transform pollutants from aquaculture water. In recirculating aquaculture systems, nitrifying bacteria convert toxic ammonia into nitrite and subsequently into the less toxic nitrate, thereby maintaining suitable water quality for cultured organisms. Biological filtration can also be supported through constructed wetlands, biofilters and beneficial microbial communities in appropriate production systems. By reducing the concentration of nitrogenous wastes and allowing partial water reuse, biofiltration can decrease effluent discharge and improve resource-use efficiency. Thus, integration of effective biofiltration with appropriate feeding and water-quality management can contribute significantly to environmentally sustainable aquaculture.

Wastewater and effluent treatment

Effective treatment of wastewater and aquaculture effluents is essential for reducing the release of organic matter, nutrients, suspended solids, chemicals and other pollutants into receiving water bodies. Effluent treatment systems can include sedimentation, filtration, biological treatment and constructed wetlands, depending on the type and intensity of aquaculture production. These processes help reduce the concentrations of nitrogen, phosphorus, organic matter and suspended particles before discharge. In intensive and recirculating systems, treated water can also be reused, thereby reducing water consumption and the volume of effluent released into the environment. Regular monitoring of effluent quality and appropriate treatment before discharge can therefore help maintain surrounding water quality and reduce the environmental impacts of aquaculture.

Integrated and ecosystem-based pollution management

Integrated pollution management combines pollution prevention, efficient resource use, wastewater treatment and ecosystem-based approaches to reduce the cumulative environmental impacts of aquaculture. Management practices should consider interactions among water quality, sediments, cultured organisms, surrounding habitats and natural aquatic communities rather than addressing individual pollutants separately. Integration of appropriate stocking densities, efficient feeding, biofiltration, effluent treatment, habitat protection and responsible use of chemicals can reduce pollutant loading and improve overall environmental performance. Ecosystem-based management also supports the maintenance of ecological functions and biodiversity while allowing aquaculture production to remain compatible with the carrying capacity of the surrounding environment (Boyd *et al*., 2015).

Monitoring and regulatory measures

Regular monitoring of water and sediment quality is important for identifying pollution problems at an early stage and maintaining suitable environmental conditions for aquaculture and fisheries resources. Key parameters may include dissolved oxygen, temperature, pH, ammonia, nitrite, nitrate, phosphate, suspended solids and other relevant contaminants depending on the production system. Monitoring of antibiotic residues, heavy metals and microplastics may also be required in areas where these pollutants are of concern. Appropriate environmental standards, effluent discharge limits, responsible chemical-use practices and compliance with regulatory requirements can further reduce pollution risks. Strengthening routine monitoring, record keeping, environmental assessment and enforcement can support sustainable aquaculture development while protecting surrounding aquatic ecosystems and fisheries resources.

Conclusion

Water pollution is a major challenge to the sustainability of fisheries and aquaculture because it can deteriorate water and sediment quality, degrade aquatic habitats, reduce fish growth, reproduction and survival, and alter fish distribution, abundance and productivity. Pollutants such as excess nutrients, organic wastes, heavy metals, chemical residues, plastics and antimicrobial resistance determinants can create ecological risks through accumulation and trophic transfer, with implications for biodiversity, fisheries production, food safety and human health. Effective pollution management therefore requires a combination of efficient feed management, biofiltration, wastewater and effluent treatment, integrated ecosystem-based approaches, and regular environmental monitoring. Strengthening pollution control, responsible resource use and regulatory measures can help maintain aquatic ecosystem health, support sustainable fisheries and aquaculture production, and reduce the long-term environmental impacts of water pollution.

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BEYOND THE APPLE BELT: A SCIENTIFIC ROADMAP FOR CROP DIVERSIFICATION IN TRANS-HIMALAYAN KINNAUR

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Panoramic view of apple cultivation at Giaboong (Ropa Valley)

Highlight

Apple occupies 86% of Kinnaur's fruited area and nearly its entire fruit economy, leaving farmers exposed to rising input costs and a net approximately return of barely Rs 11 a kilogram. Drawing on the district's 2024–25 production data and its block-wise agro-climate, this article lays out a zone-specific diversification plan for Nichar, Kalpa and Pooh built around kiwi, persimmon, pear, cherry, apricot, almond and the district's own wild pistachio and olive genetic resources, backed by scientific high-density planting, hands-on canopy management training, and mini demonstration units to build farmer confidence.

Kinnaur district, tucked into the trans-Himalayan belt of Himachal Pradesh, is popularly known as India's apple bowl. Travel through its three development blocks, Nichar, Kalpa and Pooh, and the orchards on the slopes tell a story of remarkable climatic diversity, from the wet, kiwi-friendly lower valleys of Nichar to the cold desert of Pooh, where glacial melt is the only source of irrigation. Yet this very diversity, historically Kinnaur's greatest horticultural asset, has in recent years narrowed into a heavy dependence on a single crop. As this article shows using the district's own production statistics, that dependence is now exposing growers to rising input costs, market saturation and shrinking margins. A scientific, block-wise diversification strategy, matched to elevation, rainfall and temperature, can spread this risk while opening new, remunerative income streams for Kinnaur's farming community.

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Predominating apple fruit



Locally growing grape cultivars

The Economics That Demand a Rethink

The case for diversification begins with simple arithmetic already visible in Kinnaur's own markets. Apple fruit sold at around Rs 60 a kilogram often leaves the grower with a net return of only about Rs 11 a kilogram, once production and marketing costs are deducted. Persimmon, by contrast, has shown a markedly lower input burden wherever it is already grown commercially in the district. This is not an argument against apple, which will remain Kinnaur's mainstay crop and its single largest contributor to farm income. It is an argument for building complementary orchards of crops that ask less of the farmer's purse while opening new markets.

Ground Truth, What the 2024–25 Production Data Shows

Departmental figures for 2024–25 (Table 1) put hard numbers behind this argument. Of the 12,656 ha under fruit cultivation in Kinnaur, apple alone occupies 10,937 ha, 86% of the district's fruited area and contributes 96,637 MT of the district's total fruit output of 97,439 MT, at a productivity of 8.84 MT/ha. Block-wise, apple productivity is highest in Pooh (10.35 MT/ha), followed by Kalpa (8.51 MT/ha) and Nichar (7.64 MT/ha), confirming the superior colour, firmness and quality that Pooh's dry, high-UV climate imparts to the fruit. The figures for diversification crops tell a second, equally important story. Almond occupies the second-largest area in the district, 932 ha, but yields only 149 MT, a productivity of just 0.16 MT/ha. Apricot, on 324 ha, manages 367 MT (1.13 MT/ha). Kiwifruit and persimmon show the clearest signal of all: kiwifruit covers 6.7 ha district-wide, but its entire recorded production of 2.97 MT comes from Nichar, with Kalpa and Pooh showing planted area but zero harvest. Persimmon follows the same pattern, 22.7 ha planted across all three blocks, yet only Nichar's 10.6 ha has come into bearing, yielding 8.14 MT, while Kalpa's and Pooh's plantings show none.

This is not a verdict against these crops; it is a diagnosis. Zero production on planted area signals young, not-yet-bearing orchards rather than crop failure, and confirms that kiwi and persimmon cultivation in Kinnaur remains in its infancy outside Nichar. The low productivity recorded for almond and apricot points to scattered, non-scientific plantings rather than any inherent unsuitability. Read together, the data makes the case for scientific intervention, not abandonment: farmer interest and planted area already exist; what is missing is quality planting material, correct spacing, and disciplined aftercare.

Table 1. Fruit-wise area, production and productivity in Kinnaur district, block-wise, 2024–25

Fruit	Kalpa Area (ha)	Kalpa Prodn (MT)	Nichar Area (ha)	Nichar Prodn (MT)	Pooh Area (ha)	Pooh Prodn (MT)	District Area (ha)	District Prodn (MT)	District Prodvty (MT/ha)
Apple	4028.84	34305.07	3381.81	25833.99	3526.77	36497.44	10937.42	96636.50	8.84

Fruit	Kalpa Area (ha)	Kalpa Prodn (MT)	Nichar Area (ha)	Nichar Prodn (MT)	Pooh Area (ha)	Pooh Prodn (MT)	District Area (ha)	District Prodn (MT)	District Prodvty (MT/ha)
Apricot	100.33	45.00	72.13	6.53	151.92	315.00	324.38	366.53	1.13
Almond	241.34	23.50	72.76	0.81	618.08	125.00	932.18	149.31	0.16
Walnut	79.51	46.25	43.89	10.35	95.35	47.00	218.75	103.60	0.47
Pear	34.66	70.00	31.88	12.75	13.97	7.20	80.51	89.95	1.12
Kiwifruit	1.90	0.00	2.02	2.97	2.79	0.00	6.71	2.97	0.44
Persimmon	8.01	0.00	10.62	8.14	4.11	0.00	22.74	8.14	0.36
All Fruits	—	—	—	—	—	—	**12655.75**	**97438.70**	**7.70**

Source: Department of Horticulture, Kinnaur.

Reading the Climate, A Zone-wise Basis for Crop Choice

Diversification planning must start with agro-climatic data, not sentiment alone. The Himachal Pradesh Department of Agriculture's Agro-Ecological Zone classification maps closely onto Kinnaur's elevation-driven diversity. Zone 3.1 (1,501–2,500 m, ≤1,500 mm rainfall, shallow loamy acidic soils) supports wheat, temperate vegetables and apple, and matches the lower and mid elevations of Kalpa and Nichar. Zone 4.1 (2,501–3,250 m, under 700 mm rainfall, shallow sandy loams) officially lists apple, dry fruits, hops, cumin and saffron as suited crops, a reminder that Kinnaur's higher, drier pockets in upper Kalpa and lower Pooh carry recognised potential for high-value spice crops beyond fruit. Zone 4.2 (3,251–4,250 m, dry or snow-fed, shallow sandy loams) supports quality seed potato, temperate vegetables, barley, buckwheat and wheat, closely matching the high, arid stretches of Pooh.

Station-level weather records sharpen this picture further. Kalpa and Rekong Peo average around −11°C in December, with rainfall of roughly 57 mm and about 8 hours of sunshine a day even in mid-winter, well within range for kiwi, persimmon, pear and cherry at the lower elevations of these blocks. Nako, representing Pooh, averages around −17°C in December, with rainfall dropping to about 22 mm and humidity as low as 49–60%: unmistakably dry, cold-desert territory. This explains why apple performs exceptionally here, high anthocyanin colour, thick cuticle, high TSS and firm flesh are classic responses to high UV, low humidity and wide diurnal temperature swings and why alternatives for this belt must be drought- and cold-hardy species.

A Block-wise Diversification Blueprint

Nichar block

Nichar, the wettest and lowest of the three blocks, is best suited to kiwi and persimmon alongside its existing apple orchards, and is already the only block with bearing plantations of both, as Table 1 confirms. Wild persimmon, locally called chaura dakh or amlok, grows naturally around Chaura, Nichar, Chota Kambha and Bada Kambha, an existing local adaptation that gives formal cultivar introduction a head start rarely available elsewhere. Selection of superior local types alongside improved commercial cultivars should be pursued together.

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Kiwi in fruiting at lower



Locally growing wild persimmon

Kalpa block

With 4,029 ha already under apple, the largest area of the three blocks, Kalpa needs an elevation-tiered approach for everything planted alongside it: kiwi, persimmon, pear and cherry at lower elevations, and persimmon, pear and cherry (without kiwi, whose water demand and cold sensitivity limit it at height) higher up. Pockets within Kalpa still lack organised apple cultivation and warrant scientifically laid-out high-density plantations on vigorous clonal or seedling rootstocks, in a rectangular system with wide row-to-row and minimal plant-to-plant spacing. This geometry deliberately preserves permanent alleyways for the field crops, ogla, fafra, rajmash, pea, potato and barley, that farmers already depend on, so orchard establishment does not come at the cost of food and fodder security.

Pooh block

Pooh already records the district's highest apple productivity (10.35 MT/ha), so farmer reluctance to diversify is understandable. The entry point here is risk-spreading, not replacement: apricot, almond, persimmon and kiwi for the lower-lying pockets, and apricot, prune, cherry and plum elsewhere. Water-efficient stone fruits are a natural fit for this arid belt, and their lower cultivation intensity compared to apple offers a genuine cushion, a cushion the current near-zero productivity of almond (0.20 MT/ha) and apricot (2.07 MT/ha) in Pooh suggests has not yet been realised, again pointing to scattered rather than scientific plantings.

Across all three blocks, the greatest untapped potential lies in areas where apple cultivation is only now taking hold under a warming climate, Rupi valley villages such as Shigarcha, Majhgaon, Gurguri and Dabling in Nichar; Chota Kambha and Bada Kambha; Rakcham, Mastarang and Chitkul in Kalpa; and Kuno Charang, Chulling, Hango, Nako, Malling and Tashigang in Pooh. Plantations here remain largely unscientific and fruit size stays small, but these are precisely the areas where mini demonstration units and front-line demonstrations of new fruit crops can do the best, seeing a well-managed orchard perform is what ultimately shifts farmer confidence.

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Apple new improved cultivars



Locally growing grape cultivars

Reclaiming Two Forgotten Species, Pistachio and Olive

Kinnaur's hills also carry wild populations of two crops never developed to commercial scale, and neither appears in the district's current fruit statistics, underlining how nascent their cultivation remains. Wild pistachio, locally called tirak, occurs at lower elevations of Moorang and Jangi in Pooh block; wild olive has been recorded at Kilba and Karcham in Kalpa block and Ramni in Nichar block. Olive cultivation was earlier attempted at PCDO Kilba but did not succeed commercially, and only wild relatives remain today. Pistachio multiplication faces a specific technical bottleneck: grafting failure has restricted growers to seedling material only, limiting uniformity and yield. Both crops merit a fresh, targeted trial, introducing improved cultivars precisely where their wild relatives already thrive, the strongest available evidence of climatic suitability.

Canopy Management, The Unglamorous Foundation of Quality

No diversification plan will deliver on its promise without parallel investment in basic orchard science, and none is more neglected in Kinnaur than training and pruning. Canopy management is rarely performed by the orchardist personally; it is delegated to hired pruners, and without hands-on knowledge the grower has no basis to correct or question the work being done. Training and pruning are a craft learned through repetition as much as a science learned from principle, so awareness campaigns alone will not build this skill. Field demonstration programmes need to build in actual pruning practice for farmers and pruners together, a well-managed canopy remains the single most important determinant of fruit quality and productivity in every temperate fruit crop in the district, new or old.

Adapting Harvest Practice to a Dry Climate

One further, often overlooked, aspect of Pooh's dry temperate climate deserves attention in extension messaging: harvest timing must differ from wetter regions. In the dry belt, apricot and almond reach fuller maturity and better quality than in wetter, lower-elevation conditions, where rain at the maturity stage can ruin the crop and strip it of market value. Growers in wetter pockets are accordingly advised to harvest apricot as maturity begins, rather than let it fully ripen on the tree, and to harvest almonds at the green stage before splitting begins.

Summary

Kinnaur's diversity of elevation and climate, from the wet valleys of Nichar to the cold desert of Pooh, is not a constraint on horticultural planning; it is the resource on which a resilient, multi-crop future can be built. The district's own 2024–25 statistics make the case plainly: with 86% of fruited area and nearly the entire fruit economy resting on apple, and alternative species present on the

ground but yet to bear fruit at scale, the window for organised intervention is now. Apple will remain central to Kinnaur's horticultural identity, but pairing it with persimmon, kiwi, pear, cherry, apricot, almond, and the district's own underused pistachio, olive, hops, cumin and saffron potential, planted to elevation-specific climatic suitability and demonstrated first through mini demo units and front-line demonstrations, offers a realistic path to lower input costs, spread market risk, and a stronger economic footing for Kinnaur's farming community.

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