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Tandel and Bamaniya (2026)

Fish as Food: A Nutritional and Functional Superfood for Human Health

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Abstract

Fish is considered one of the most nutritious foods for human health due to its rich composition of proteins, omega-3 fatty acids, vitamins, minerals and bioactive compounds. Fish proteins possess high digestibility and contain all essential amino acids required for growth, tissue repair and maintenance of body functions. Fish lipids are rich in omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which contribute significantly to cardiovascular protection, brain development, anti-inflammatory responses and neurological health. Fish also contains important micronutrients including calcium, selenium, iodine, iron, phosphorus, zinc and vitamins A and D that support bone health, immunity, thyroid function, blood formation and metabolic regulation. Recent studies have further highlighted the role of fish-derived bioactive compounds and peptides that possess antioxidant, antimicrobial, antihypertensive, neuroprotective and wound-healing properties. In addition to its nutritional importance, fish contributes significantly to food security, livelihood generation and sustainable nutrition globally. Despite these benefits, fish consumption remains low in several developing countries because of lack of awareness and dietary preferences. Therefore, increasing awareness regarding the health and nutritional significance of fish can improve public health and nutritional security worldwide.

Keywords: Fish Nutrition, Omega-3 Fatty Acids, Functional Food, Bioactive Compounds, Human Health

1. Introduction

Fish has been an important source of food and nutrition for humans since ancient times and continues to contribute significantly to global nutritional security (Tacon & Metian, 2013). Fish is widely recognized as one of the healthiest animal protein sources because it contains highly digestible proteins, essential fatty acids, vitamins, minerals and biologically active compounds that are beneficial for human health (Yadav et al., 2025: Mehta et al., 2025). Compared to terrestrial animal meat, fish contains lower amounts of saturated fats and higher levels of polyunsaturated fatty acids, especially omega-3 fatty acids, making it nutritionally superior for maintaining health and preventing chronic diseases (Mozaffarian & Rimm, 2006). Fish consumption has increased globally due to growing awareness about its nutritional value and therapeutic properties. Fish not only provides essential nutrients but also contributes to prevention of cardiovascular diseases, obesity, hypertension, inflammatory disorders, arthritis, osteoporosis and neurological diseases such as Alzheimer’s disease and Parkinson’s disease (Li et al., 2020). According to Balami et al. (2019), fish is often referred to as “rich food for poor people” because it provides affordable, high-quality nutrition with excellent digestibility.

The nutritional composition of fish varies depending on species, feeding behavior, habitat, environmental conditions, season and whether the fish is farmed or wild-caught. However, most fish species contain abundant proteins, lipids, vitamins and minerals that are essential for growth, metabolism, tissue repair and maintenance of body functions (Mohanty, 2015). Fish proteins contain all essential amino acids including lysine, methionine and cysteine, which are often limited in plant-based diets (Pal et al., 2018). Recent studies have also identified fish as a functional food because fish-derived compounds exhibit antioxidant, antimicrobial, anti-inflammatory, antihypertensive and neuroprotective activities (Ryan et al., 2011). Marine bioactive peptides derived from fish skin, muscle, bones and hydrolysates are now increasingly used in pharmaceutical and nutraceutical industries due to their therapeutic importance.

2. Nutritional Composition of Fish

Fish contains both macronutrients and micronutrients that are necessary for maintaining healthy body functions and metabolic activities. The proximate composition of fish generally includes 15-20% protein, 5-20% fat, 65-80% moisture and 0.5-2% minerals and ash content (Mohanty, 2015). This balanced nutrient composition makes fish one of the most nutritious foods available for human consumption. Fish proteins are classified as high biological value proteins because they contain all essential amino acids required for human growth and development (Pawar & Sonawane, 2013). Fish lipids are particularly important because they contain long-chain omega-3 polyunsaturated fatty acids such as EPA and DHA that are associated with cardiovascular and neurological health benefits (Swanson et al., 2012). Fish also provides essential vitamins such as vitamins A, D and B-complex vitamins along with minerals including calcium, phosphorus, selenium, zinc, iodine, potassium and iron (Balami et al., 2019).

Fatty fish species such as salmon, tuna, sardine and mackerel contain higher amounts of omega-3 fatty acids, whereas lean fish species provide lower fat content but still serve as excellent sources of protein and micronutrients (Mozaffarian & Rimm, 2006). According to FAO (2010), fish contributes significantly to the intake of micronutrients that are often deficient in diets of developing countries. Fish also possesses lower connective tissue content compared to red meat, which makes fish protein easier to digest and absorb (Venkatraman & Chezhian, 2015). Due to this characteristic, fish is highly recommended for children, elderly people, pregnant women and patients recovering from illness.

3. Importance of Fish Protein in Human Health

Fish is one of the richest sources of highly digestible animal protein and contributes significantly to growth, development, tissue repair and metabolic regulation. Fish protein digestibility ranges from 85-95%, which is higher than many terrestrial animal proteins due to the lower connective tissue content in fish muscle (Venkatraman & Chezhian, 2015). Fish proteins contain essential amino acids including methionine, lysine, cysteine and tryptophan that are necessary for enzyme synthesis, muscle growth, immune regulation and maintenance of body tissues (Mohanty, 2015). Fish proteins also contain immunoglobulins and bioactive peptides that provide defense against bacterial and viral infections and improve immune responses (Ryan et al., 2011).

Protein deficiency remains a major nutritional problem in many developing countries. Fish plays an important role in preventing protein-calorie malnutrition because it provides affordable and high-quality protein to economically weaker populations (FAO, 2010). According to Balami et al. (2019), a 140 g serving of fish can provide nearly 50-60% of the daily protein requirement for adults. Several studies have reported that regular fish consumption helps maintain muscle mass, electrolyte balance, healthy blood circulation and proper metabolic functions (Pawar & Sonawane, 2013). Fish proteins are also important in maintaining satiety and supporting healthy body weight management compared to other animal proteins (Bogati, 2018).

4. Omega-3 Fatty Acids and Their Health Benefits

One of the most important nutritional characteristics of fish is the presence of omega-3 polyunsaturated fatty acids, especially EPA and DHA. These fatty acids play essential roles in cardiovascular protection, neurological development, inflammation control and maintenance of cellular functions (Swanson et al., 2012). Numerous studies have demonstrated that omega-3 fatty acids reduce plasma triglyceride levels, regulate blood pressure, improve blood circulation and reduce platelet aggregation, thereby lowering the risk of cardiovascular diseases and coronary heart disease (Bucher et al., 2002). Regular fish consumption has also been associated with lower incidences of heart attack, arrhythmia and stroke (Mozaffarian & Rimm, 2006).

DHA is particularly important for brain and nervous system development in infants and children (David, 2013; Yadav et al., 2025). During pregnancy and lactation, omega-3 fatty acids support fetal brain development and visual function. EPA and DHA also contribute to memory improvement, cognitive performance, and neuroprotection against diseases such as Alzheimer’s disease and Parkinson’s disease (Butt & Salem, 2016).

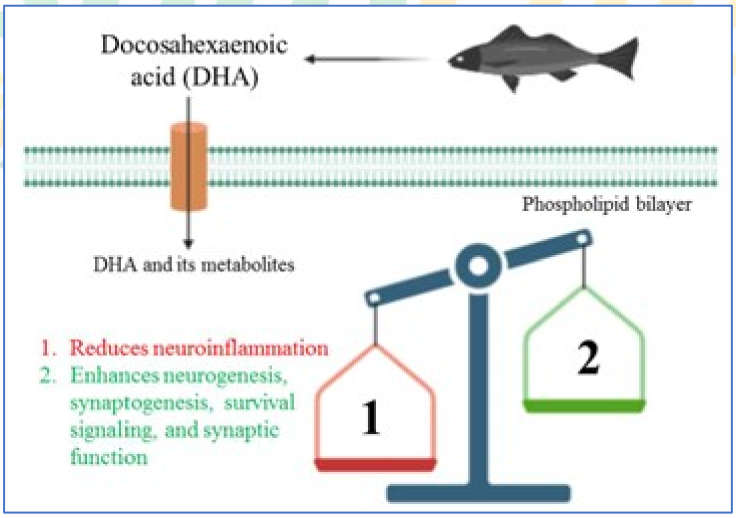

Fig. 1 Neuroprotective action of DHA obtained from fish

Fish oils possess strong anti-inflammatory properties that help reduce inflammatory disorders such as arthritis, ulcerative colitis, obesity and metabolic syndrome (Wall et al., 2010). Omega-3 fatty acids reduce oxidative stress and inflammatory cytokine production, thereby improving overall health and immunity.

5. Vitamins and Minerals Present in Fish

Fish is an important natural source of vitamins and minerals that are essential for human growth, metabolism and immunity (Balami et al., 2019). Fish provides significant amounts of vitamins A, D and B-complex vitamins, all of which are important for maintaining healthy physiological functions. Vitamin A supports vision, bone development, epithelial tissue maintenance, immune function and cellular growth (Pal et al., 2018). Vitamin D present in fish and fish oils plays a critical role in calcium absorption, bone mineralization and prevention of osteoporosis, osteomalacia and rickets (Holick & Chen, 2008).

Fish also supplies important minerals such as calcium, phosphorus, iron, selenium, zinc, iodine and potassium. Calcium and phosphorus contribute to bone strength and metabolic activities, while iron is necessary for hemoglobin synthesis and oxygen transport in blood . Selenium acts as an antioxidant and supports thyroid gland function, whereas iodine is essential for hormone synthesis and metabolic regulation (Holben & Smith, 1999). Small indigenous fish species consumed with bones are excellent sources of calcium and micronutrients and contribute significantly to nutritional security in rural populations.

6. Fish as Functional Food

In recent years, fish has gained attention as a functional food because it provides health benefits beyond basic nutrition (Ryan et al., 2011). Fish-derived peptides and bioactive compounds possess antioxidant, antimicrobial, antihypertensive, anti-inflammatory and neuroprotective activities that contribute to disease prevention and healthy aging (Sila & Bougatef, 2016).

Marine bioactive peptides isolated from fish skin, muscle, bones and hydrolysates have demonstrated strong antioxidant properties by reducing oxidative stress and protecting cells against free radical damage. Fish-derived antimicrobial peptides also inhibit the growth of pathogenic microorganisms and strengthen immune defense mechanisms (Ryan et al., 2011). Fish oils and peptides have shown beneficial effects in wound healing and tissue repair by regulating inflammation and collagen synthesis (McDaniel et al., 2008). Due to these therapeutic properties, fish-derived compounds are increasingly being utilized in pharmaceutical, cosmetic and nutraceutical industries.

Recent studies have also suggested that bioactive compounds from fish may help regulate hypertension, diabetes, inflammatory disorders and neurodegenerative diseases (Li et al., 2020). Therefore, fish is now recognized not only as a nutrient-rich food but also as a valuable source of functional ingredients for promoting human health.

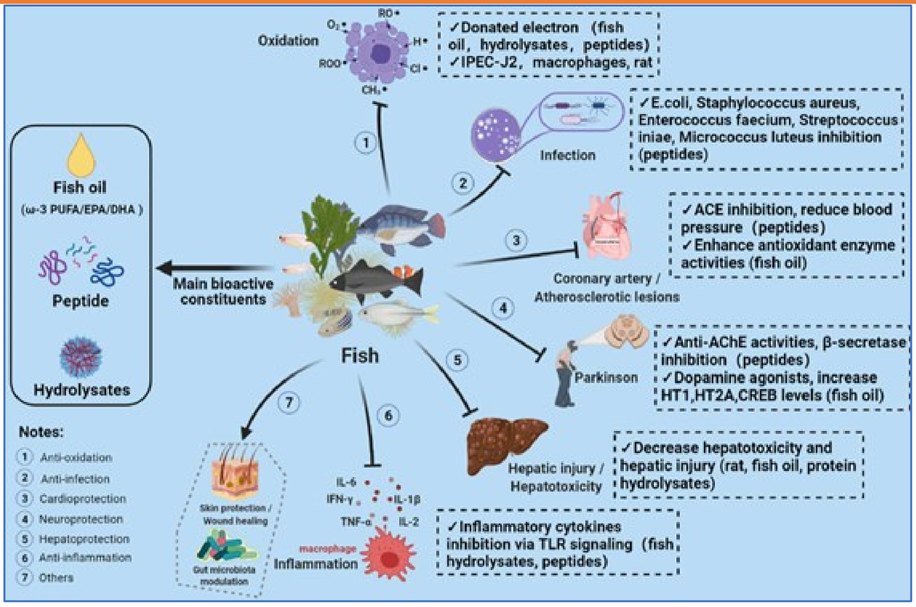

Fig. 2 Health benefits of fish consumption and their corresponding bioactive constituents

7. Conclusion

Fish is one of the most valuable foods for human nutrition because it provides high-quality proteins, essential fatty acids, vitamins, minerals and bioactive compounds that contribute significantly to human health and disease prevention. Fish proteins support growth, tissue repair, immunity and prevention of protein-calorie malnutrition, while omega-3 fatty acids such as EPA and DHA play major roles in cardiovascular protection, neurological development and inflammation control. Fish also serves as an important source of vitamins A and D along with essential minerals such as calcium, iron, selenium and iodine that are required for bone health, thyroid function, blood formation, metabolism and immunity. In addition, fish-derived bioactive peptides exhibit antioxidant, antimicrobial, anti-inflammatory, antihypertensive and neuroprotective activities that make fish an important functional food for healthy aging and disease prevention. Despite its nutritional and therapeutic importance, fish consumption remains lower than recommended levels in many regions due to lack of awareness and dietary habits. Therefore, increasing awareness regarding the health benefits of fish and promoting sustainable fisheries and aquaculture development can significantly improve nutritional security, public health and economic growth worldwide.

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The Brackish Revolution: Redefining Women's Roles in Coastal Aquaculture

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Abstract

Coastal aquaculture plays a vital role in India's blue economy by utilizing saline and brackish water resources for the culture of shrimp, fish, crabs, and other aquatic organisms. Despite possessing vast coastal and estuarine resources, only a small proportion of India's brackish water potential is currently utilized. Recent initiatives by the Indian Council of Agricultural Research–Central Institute of Brackish water Aquaculture (ICAR-CIBA) and government schemes have significantly enhanced women's participation in aquaculture production, entrepreneurship, and leadership. Women-led interventions in Andhra Pradesh, Tamil Nadu, Odisha, Maharashtra, and West Bengal have demonstrated improved income generation, sustainable resource utilization, and ecosystem conservation. Integrated farming systems such as shrimp–seaweed culture, mud crab farming, and integrated shrimp–rice farming have strengthened livelihood security and climate resilience. However, challenges including limited access to resources, inadequate representation in decision-making, and socio-cultural barriers continue to hinder women's full participation. Strengthening gender-inclusive policies, capacity building, and institutional support can accelerate sustainable coastal aquaculture development. The empowerment of women in brackish water aquaculture represents a transformative pathway toward inclusive growth, environmental sustainability, and resilient coastal communities in India.

Keywords: Coastal Aquaculture, Brackish Water Farming, Women Empowerment, Blue Economy, Sustainable Livelihoods, Climate Resilience

Introduction: A Silent Change along the Coasts of India

Coastal area is the area of land within a distance of two km from the high tide line of the seas, rivers, creeks and back water. Coastal aquaculture mainly includes culturing under controlled conditions in ponds, pens, enclosures in coastal areas, of shrimp, prawn fish or any type of other aquatic species in saline or brackish water. Brackish water aquaculture occupies a unique position, acting as a bridge between inland and marine aquaculture. It is most commonly classified under coastal aquaculture. According to Hand book of fisheries statistics, 2025 India's overall fish output expanded at an average annual rate of 6.47%, driven by inland fisheries, which grew 7.69% per year and marine at 3.05%. In India mariculture activities are confined only to coastal brackish aquaculture, mainly shrimp farming. There is about 1.2 million ha are suitable for land based saline aquaculture but only 15% is utilized. In India there are about 3.9 million ha area of estuaries, 0.58 million ha area of mangroves and has revised coastline of 11,098.81km presenting a major frontier of economic and export growth. World's second largest producer produce roughly 75% of its total output comes from inland aquaculture not from the ocean, even though mariculture has a potential to augment seafood production in the context of decline catch rate from the capture fisheries in India.

There is a need of transformation in this sector now focus should not just the economic output but it's who is leading it. In many coastal communities, men explained that women were told to focus on processing rather than production because of the hard work involved from launching into deep water, setting trap for fish pulling the boat back to shore. Now we all know the condition near shore waters facing like serious over fishing, highly explored and resource depletion. India lack the advanced refrigeration, navigation and heavy-duty gear required to harvest at deep sea depth. Addressing the challenge faced by the traditional fishing brackish revolution is necessary to improve balance between fish production and environmental sustainability. Brackish revolution also solves the problem because it is physically accessible and safer for women in coastal regions like Andhra Pradesh, Tamil Nadu and Odisha. The shift began when ICAR-CIBA (Central Institute of Brackish water Aquaculture), headquartered in Chennai, began actively training women in brackish water farming technologies.

Cultural norms across India have confined women to essential and undervalued work but a small initiative is creating economic pathways for women who have long been marginalized in the sector. Over 12.4 million women now participate in India's fisheries and seafood sector, moving beyond traditional post-harvest roles into farm ownership, management, and entrepreneurship.

Indian Coastal Communities: Transitioning from Invisible Labor to Visible Leadership

In the year 2021 ICAR-Central Institute of Brackishwater Aquaculture (CIBA), with the STC/TSP and SCSP schemes initiated two interventions "Diversification of livelihoods among coastal Scheduled Tribal families and Scheduled Caste Families through brackishwater aquaculture technologies. which opened the door for many women and children. After that Women group of Tamil Nadu named 'Velu Nachiyar Irular Tribal women group' are now pioneering example in mud crab farming at tide fed ponds with the help of ICAR-CIBA initiative program. This program's success led trained women self-help group to demonstrate crab stocking, handling and feeding to new beneficiaries. MSSRF (M.S. Swaminathan Research Foundation) partnered with CIBA in other districts of Tamil Nadu named Cuddalore and Myladuthurai districts are also implement aquaculture-based livelihood project for coastal women. These women are now earning more than their previous income from casual labor by farming mud crabs in mangrove pens. United Nations has declared 2026 as the 'UN year for women farmers' highlighted opportunities availability and appreciate importance of women folk in fisheries and aquaculture. Recently on the occasion of women's day-2026, ICAR-CIBA reinforced awareness on women's empowerment and felicitated about 30 fisher women self-help groups while recognizing the value, contributions of women in fisheries and aquaculture sector.

Another project for scientific mud crab farming named Enhancing Climate Resilience of India's Coastal Communities (ECRICC) initiated under Rajiv Gandhi Centre for Aquaculture (RGCA), Chennai at odisha. Currently, over 304 women Climate Champions are supporting crab farming activities in Ganjam, Balasore, Kendrapara, and Puri. These women not only cultivate organically but also train others, marking a grassroots-led success model. With 70% of the input costs subsidised, the project ensures inclusive access to sustainable aquaculture.

State-Level Economic Transformation in Coastal Aquaculture

Andhra Pradesh: using ICAR-CIBA's seaweed shrimp integration model (an IMTA strategy), a women's cooperative in east Godavari now owns and runs 150 hectares of shrimp farms that were previously under male management, increasing productivity by 20%. Culturing shrimp with seaweed, which enhances water quality, lowers the risk of disease, and generates additional seaweed revenue; thirty SHG women reported 3–8× higher yields.

Tamil Nadu: Thirteen women entrepreneurs from Thoothukudi, Nagapattinam, and Ramanathapuram now operate across multiple high-value nodes of coastal aquaculture—including shrimp and crab farming, hatchery management, and export-oriented value chains. Identified as role models in fieldwork conducted for this study, these women demonstrate trajectories from labour participation to firm ownership and sectorial leadership. Their experiences suggest that improved access to technology, credit, and market linkages can enable women to occupy higher-value positions within coastal aquaculture value chains.

Maharashtra: Eleven women's self-help groups in Ratnagiri and Sindhudurg farm green mud crab in mangrove pens. They earn between Rs. 30,000 and Rs. 83,000 each season while conserving 28.5 acres of mangroves. Dirbanarayan self-help group doubled its seasonal income from Rs. 42,000 to Rs. 83,000 in just one year. This model connects income generation with mangrove conservation. It shows how women's teamwork can match financial benefits with caring for ecosystems in coastal areas. This supports research on women's cooperatives improving sustainability in small-scale fisheries and mariculture.

West Bengal: Women in the Sundarbans developed an integrated shrimp-rice farming method, recognized by FAO, across 29.84 hectares with 42 farmers. They achieved double the profits of traditional aquaculture while keeping 5 to 30% mangrove cover and bringing back local rice varieties. This system merges aquaculture with agriculture and mangrove protection, providing a climate-resilient livelihood strategy in a delicate delta. The case highlights the vital role of women in maintaining agro biodiversity and supporting gender-responsive coastal aquaculture that addresses climate change.

This demonstrate that the blue economy of India can only be truly inclusive, equitable and sustainable if it acknowledges and rewards the invisible labor women do as essential components of an entrepreneurial leadership team. But barriers still persist in terms of decision-making authority, institutional bottlenecks in relation to co-governance, socio-cultural marginalization, poverty inhibiting access to capital and a range of interconnected system-wide challenges that can only be solved through transformative solutions framed within a holistic systems approach.

Gender Inclusive Policy and Farming Model in India For Fisheries and Aquaculture

The back bone of India’s fisheries and aquaculture sector is Pradhan Mantri Matsya Sampada Yojana (PMMSY), a scheme that delivering 60% financial assistance to women beneficiaries. Through its Entrepreneur Model, women can also get access up to ₹1.50 crore subsidy on ₹5.00 crore project costs for integrated aquaculture ventures. From 2020–21 to 2024–25, ₹4,061.96 crore benefited 99,018 women nationally, including 11,642 in Tamil Nadu where seaweed farming operates on mission mode. Complementing this, PM-MKSSY offers women-led microenterprises a 35% Performance Grant (₹45 lakh ceiling). The National Fisheries Development Board has trained 5,000+ women in entrepreneurship, enabling transition from labor participation to value-chain ownership. India's brackish water coastal regions present special chances for locally tailored Integrated Multi-Trophic Aquaculture (IMTA), with women farmers spearheading creative integrated systems. Using poultry waste as fertilizer for phytoplankton growth, women in Andhra Pradesh's Krishna and Guntur districts combine shrimp farming with backyard poultry to increase household income by 35%. ICAR-CIBA provides gender-specific technical manuals for this sustainable technology, and women in Tamil Nadu's Pichavaram and Odisha's Bhitarkanika raise mud crabs in raised pens within mangrove ecosystems without destroying these vital habitats. In the Gulf of Mannar region of Tamil Nadu, pilot projects teach women how to grow seaweed for use in food, cosmetics, and bioplastics.

Challenges Faced by Women and Its Mitigation

Gender-Blind Statistics, Limited access to resources, limited participation of coastal women in decision-making, co-governance, and leadership Intensification Displaces Women due to low level of literacy, Double Burden and institutional bottle necks (for example limited participation coastal women in decision-making, co-governance, and leadership) are the major common issues faced by women. The Brackish Revolution's next phase in India requires intentional action on multiple fronts. Focused policy measures, consistent gathering of data broken down by sex, embedding gender equality and decent work criteria into certification processes, bolstering cooperatives led by women, aiding female entrepreneurship in the fisheries sector, and enhancing scholarship and vocational training initiatives will enhance women's involvement, leadership roles, and economic empowerment, thereby fostering a more sustainable and equitable aquaculture industry in India.

Conclusion

The Promise of Brackishwater is not just a success story; it's about creating new livelihoods and pathways to better nutrition, by turning coastal and brackish water resources into engines of livelihood and women as farmers, entrepreneurs and leaders. While hurdles remain, including the lack of adequate gender-disaggregated data and poor institutional recognition, the momentum is undeniable. If supported through the initiatives of ICAR-CIBA, MPEDA, and Department of Fisheries these women are set to lead the next wave of sustainable aquaculture in India, where something other than pure production is recognised as a marker for success—the empowerment will be easier to scale up way ahead if we can define its nexus with true environmental sustainability.

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Delivering Bioactive Compounds to Fish Larvae Using Microencapsulated Diets

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Abstract

The successful rearing of fish larvae is one of the greatest challenges in modern aquaculture due to the difficulty of delivering essential nutrients and bioactive compounds to the developing digestive system of larvae. Microencapsulated diets have emerged as an innovative approach for improving nutrient stability, reducing leaching losses, and ensuring effective delivery of biologically active substances. This article discusses the role of microencapsulation technology in transporting important bioactive compounds such as hormones, amino acids, and vitamins into fish larvae. Protein-walled microcapsules are designed to retain nutrients in water while remaining digestible to larval fish after ingestion. Studies on gilthead seabream (*Sparus aurata*) and Senegal sole (*Solea senegalensis)* demonstrated successful incorporation of estradiol, lysine, and vitamin C into larval tissues through microencapsulated diets. The technology showed high retention efficiency for amino acids and effective delivery of hormones and vitamins, although encapsulation efficiency and growth responses varied among compounds. Microencapsulated feeds also offer advantages such as reduced nutrient wastage, improved water quality, and the possibility of partial replacement of live feeds. However, challenges including nutrient leaching, low incorporation efficiency, and incomplete digestive utilization still limit full commercial application. Despite these limitations, microencapsulation represents a promising strategy for precision larval nutrition and functional feed development in aquaculture. Future advancements in encapsulation techniques may further improve larval growth, survival, immunity, and sustainability in fish hatchery systems.

Keywords: Microencapsulation, Fish larvae, Bioactive compounds, Microencapsulated diets, Larval nutrition

Introduction

Modern aquaculture depends heavily on the successful rearing of healthy fish larvae. During the early stages of life, fish larvae require highly digestible nutrients and biologically active compounds for proper growth, survival, immunity, and organ development. However, delivering these substances effectively to tiny larvae has always been a major challenge because their digestive system is still immature and conventional dry feeds often lose nutrients rapidly in water. The application of microencapsulated diets in larval aquaculture offers several important advantages. It improves nutrient retention, enhances feed stability, reduces nutrient wastage, and allows precise incorporation of biologically active compounds into larval diets. Bioactive compounds such as vitamins, free amino acids, hormones, enzymes, probiotics, and immunostimulants play significant roles in promoting growth, enhancing immunity, improving stress resistance, and supporting proper physiological development in fish larvae. Effective delivery of these compounds is therefore essential for improving larval survival and overall hatchery performance.

Recent studies have demonstrated that protein-walled microcapsules can successfully deliver compounds such as estradiol, lysine, and vitamin C into marine fish larvae including gilthead seabream (*Sparus aurata*) and Senegal sole (*Solea senegalensis*). Therefore, the development of efficient microencapsulated diets has become an important area of research for improving fish larval rearing techniques, enhancing hatchery productivity, and supporting sustainable aquaculture practices worldwide.

Why Bioactive Compounds Are Important in Fish Larvae

The larval stage is the most delicate and sensitive phase in the life cycle of fish. During this period, fish larvae undergo rapid growth, organ formation, skeletal development, and immune system maturation. To support these complex physiological processes, larvae require not only basic nutrients such as proteins and lipids but also a range of bioactive compounds that actively regulate growth and health. Bioactive compounds including vitamins, amino acids, hormones, enzymes, probiotics, and immunostimulants play a vital role in improving digestion, boosting immunity, enhancing stress tolerance, and promoting proper metabolic functions.

Unlike juvenile or adult fish, larvae possess an immature digestive system that cannot efficiently utilize conventional feeds. Therefore, even minor nutritional deficiencies during this stage can lead to poor growth, deformities, weak immunity, and high mortality. Bioactive compounds help bridge this nutritional gap by supporting cellular development and improving nutrient utilization. For example, amino acids are essential for tissue formation, vitamins act as antioxidants and metabolic regulators, while hormones influence growth and developmental processes.

In modern aquaculture, the effective delivery of these compounds has become increasingly important for achieving better larval survival and hatchery success. Proper supplementation of bioactive substances can enhance larval quality, improve disease resistance, and ultimately contribute to sustainable and profitable fish production.

Concept of Microencapsulated Diets

Imagine a tiny protective package carrying essential nutrients directly to a fish larva. This is the basic concept behind microencapsulated diets. Microencapsulation is a feed technology in which nutrients and bioactive compounds are enclosed within microscopic capsules made of proteins, lipids, or other biodegradable materials. These miniature capsules act like protective shields, safeguarding valuable nutrients from dissolving into the surrounding water before they are consumed by the larvae.

The technology was developed to address one of the major challenges in larval aquaculture—nutrient loss through leaching. Since fish larvae feed slowly and possess an immature digestive system, conventional feeds often lose vitamins, amino acids, and other water-soluble compounds before ingestion. Microencapsulated diets overcome this problem by retaining nutrients within a stable outer wall while remaining sufficiently digestible once inside the larval gut.

Beyond simple nutrient delivery, microcapsules function as intelligent carriers capable of transporting a wide range of bioactive compounds, including vitamins, hormones, amino acids, probiotics, enzymes, and immunostimulants.

The advantages of microencapsulated diets include:

- Reduced nutrient leaching
- Better stability in water
- Controlled release of nutrients
- Improved ingestion by larvae
- Ability to carry multiple bioactive compounds simultaneously

These characteristics make microcapsules suitable carriers for larval nutrition studies and commercial hatchery operations.

Delivery of Hormones Through Microcapsules

Hormones act as nature's biological messengers, controlling many vital processes in fish larvae, including growth, development, metabolism, and physiological adaptation. Delivering these sensitive compounds to tiny larvae, however, is a significant challenge because hormones can be easily lost in water or degraded before reaching their target tissues. Microencapsulation technology offers an effective solution by enclosing hormones within protective microscopic capsules that safeguard them during feeding and transport them directly to the larval digestive tract.

Once ingested, the capsule wall gradually breaks down, releasing the hormone in a controlled manner where it can be absorbed and utilized by the larva. Research has shown that microencapsulated diets successfully delivered the hormone 17β-estradiol to gilthead seabream larvae, with measurable amounts detected in larval tissues shortly after feeding. This demonstrated that microcapsules can function as efficient vehicles for oral hormone administration in fish larvae.As microencapsulation technologies continue to improve, hormone-enriched microdiets may become valuable tools for enhancing larval quality, understanding fish physiology, and developing advanced larval rearing strategies in modern aquaculture.

Delivery of Free Amino Acids

Free amino acids are the building blocks of proteins and play a crucial role in the rapid growth and development of fish larvae. They are involved in tissue formation, enzyme production, energy metabolism, and the development of muscles and organs. However, because free amino acids are highly water-soluble, they can quickly leach from conventional feeds into the surrounding water before the larvae have a chance to consume them, resulting in nutrient loss and reduced feeding efficiency.

Microencapsulation technology acts like a protective nutrient carrier, trapping free amino acids within tiny feed particles and preventing their premature loss. Once the microcapsules are ingested, the capsule wall breaks down in the digestive tract, releasing the amino acids where they can be efficiently absorbed and utilized by the larvae. This targeted delivery ensures that valuable nutrients reach their intended destination rather than being wasted in the culture water.

Lysine Encapsulation

Studies using lysine-enriched microcapsules demonstrated excellent nutrient retention, with most of the amino acid remaining protected even after prolonged immersion in water. Such efficient delivery systems can help improve protein synthesis, support healthy tissue growth, and enhance overall larval performance. By ensuring a reliable supply of essential amino acids during the critical early stages of life, microencapsulated diets contribute significantly to stronger, healthier, and more resilient fish larvae in modern aquaculture systems.

Amino acid delivery through microcapsules may help:

- Improve larval growth
- Enhance protein synthesis
- Reduce nutrient wastage
- Increase feed efficiency

Delivery of Vitamin C

Vitamin C Supplementation

Delivering Vitamin C to fish larvae is challenging because it is highly sensitive to water and can be lost from feed before consumption. Microencapsulation technology helps overcome this problem by enclosing Vitamin C within protective microscopic capsules that shield it from leaching and environmental degradation. These capsules preserve the vitamin until they are ingested, ensuring that a greater proportion reaches the larval digestive system.

microencapsulated forms of Vitamin C can be successfully incorporated into larval diets and absorbed by fish larvae. Although growth responses may vary depending on dietary composition and culture conditions, the technology improves the availability of this essential nutrient and supports better physiological health. By safeguarding Vitamin C and delivering it precisely where it is needed, microencapsulated diets contribute to stronger immunity, healthier development, and improved larval quality—laying the foundation for robust fish production in modern aquaculture.

Advantages of Microencapsulated Diets in Aquaculture

Microencapsulated diets offer a revolutionary approach to larval fish feeding by protecting sensitive nutrients and delivering them efficiently to developing fish larvae. These specialized feed particles not only improve nutrient utilization but also support sustainable and cost-effective hatchery operations. Their ability to carry essential nutrients and functional additives makes them an important tool in modern aquaculture.

1. Controlled Nutrient Delivery

Ability to protect nutrients from premature loss. The capsule wall acts as a protective barrier, preventing valuable compounds from dissolving into the water before consumption. Once ingested, the capsules release their contents within the larval digestive tract, ensuring maximum nutrient availability and utilization.

2. Reduced Dependence on Live Feed

The production of live feeds such as rotifers and Artemia requires considerable labor, infrastructure, and operational costs. Microencapsulated diets provide a promising alternative by supplying essential nutrients in a stable and readily available form.

3. Improved Water Quality

Nutrient leaching from conventional feeds often leads to water contamination and excessive microbial growth in rearing tanks. Microencapsulated feeds minimize nutrient losses, thereby reducing organic waste accumulation and helping maintain better water quality. Cleaner culture conditions contribute to improved larval health and lower disease risks.

4. Precise Nutritional Manipulation

Microencapsulation allows nutritionists and researchers to incorporate specific nutrients and bioactive compounds at precise concentrations. Essential amino acids, vitamins, minerals, hormones, and other functional ingredients can be accurately delivered according to the nutritional requirements of different fish species and developmental stages, enabling targeted nutritional interventions.

5. Platform for Functional Feeds

Microcapsules serve as effective carriers for a wide range of functional compounds, including probiotics, immunostimulants, digestive enzymes, vaccines, antioxidants, and therapeutic agents. This capability opens new opportunities for enhancing immunity, improving stress tolerance, promoting growth, and strengthening disease resistance in fish larvae.

Limitations of Microencapsulation Technology

Low Encapsulation Efficiency: Certain substances, especially highly water-soluble compounds, may not be efficiently trapped inside the capsule wall. Consequently, the amount of nutrient ultimately delivered to the larvae may be significantly lower than the amount originally added during feed formulation.

Nutrient Degradation During Processing: The manufacturing process can expose sensitive nutrients to physical and chemical stresses that may reduce their effectiveness. Vitamins, hormones, and other bioactive compounds can undergo degradation during encapsulation, storage, or drying, leading to a decline in their biological activity before the feed is even consumed by the larvae.

Incomplete Digestion by Larvae: Fish larvae possess an immature digestive system that is still developing during the early stages of life. As a result, they may not be able to completely break down and digest certain microcapsules. This can limit nutrient release and absorption, reducing the nutritional benefits expected from the encapsulated feed.

Variable Nutrient Leaching: Although microencapsulation greatly reduces nutrient loss compared with conventional feeds, nutrient leaching can still occur. The extent of nutrient leakage often varies depending on factors such as capsule composition, water temperature, pH, immersion time, and particle size. Excessive leaching reduces feed quality and contributes to nutrient wastage.

High Production Costs: The production of high-quality microencapsulated diets requires specialized materials, sophisticated equipment, and carefully controlled manufacturing processes. These factors increase production costs, making microdiets more expensive than conventional feeds and limiting their widespread commercial application in some hatcheries.

Conclusion

Microencapsulated diets represent a significant breakthrough in fish larval nutrition by providing an efficient and reliable means of delivering essential bioactive compounds directly to developing larvae. Through the protection of sensitive nutrients such as hormones, amino acids, vitamins, probiotics, and immunostimulants, microencapsulation minimizes nutrient losses, improves feed stability, and enhances nutrient availability during the most critical stage of fish development. These benefits contribute to better growth, stronger immunity, improved stress resistance, and higher larval survival rates. In addition to supporting larval health, microencapsulated feeds offer practical advantages such as improved water quality, reduced feed wastage, and the potential to decrease dependence on live feeds. Although challenges including low encapsulation efficiency, nutrient degradation, incomplete digestion, and high production costs still exist, continuous advancements in feed technology and encapsulation techniques are steadily addressing these limitations. As research and innovation continue, microencapsulation is expected to become an indispensable tool for precision larval nutrition, contributing to more sustainable, productive, and economically viable aquaculture systems in the future.

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Nanobiosensors and Their Emerging Applications in Fisheries and Aquaculture

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Abstract

Nanobiosensors are advanced nanoscale devices that integrate nanotechnology and biological sensing to enable rapid, sensitive detection of chemical and biological targets. They enable real-time monitoring of water quality, pathogens, fish health, and product safety in aquaculture systems. Their high sensitivity, portability, and specificity support precision farming and sustainable aquaculture management. With ongoing advancements in nanomaterials and biosensing technologies, nanobiosensors are expected to play a key role in improving productivity and environmental monitoring in fisheries and aquaculture.

Keywords: Nanobiosensors, Aquaculture, Fisheries, Water Quality Monitoring, Fish Health Management

1. Introduction

The development of nanobiosensors with incredibly focused microscopic sensors and high levels of miniaturization based on nanotechnology. It resulted from advances in science in the twenty-first century. Biosensors with remarkable sensing capabilities have recently been developed by researchers using an integrated approach that combines nanoscience, electronics, computing, and biology (Kerry et al., 2021). Nanobiosensors are actually nanosensors that have immobilized bioreceptor (Enzyme, Antibody, Protein molecule, DNA, Bacteria, or any cells, etc.) probes that are selective for the molecules of the target analyte. A nanobiosensor is often constructed at the nanoscale to collect, process, and analyze data at the atomic level (Sharma et al., 2021). Earlier bio-analytical processes were impractical, hitherto enabling actual applications and presenting new avenues for fundamental research. Its developments brought about nanoscale biosensors with exceptional sensitivity and adaptability. Its principle is based on identifying biochemical and biophysical signals associated with a particular disease at the molecular or cellular level. To make molecular diagnostics easier, it can be included in other technologies like lab-on-a-chip. Their applications include the detection of analytes like pathogens, microbes, prokaryotic cells, viral particles, urea, glucose, pesticides, etc., and the monitoring of metabolites.

2. Understanding the mechanism of Nano-biosensors

A nanobiosensor is an electroanalytical device in which a bioreceptor is incorporated into the transducer to generate measurable signals correlated with the concentration of a particular analyte in any type of sample (Bhattarai and Hameed, 2020). First, the analyte is recognized by the bioreceptor. After that, the biological material is immobilized, and a contact is then created between it and the transducer. The biological substance and the analyte combine to form a bound analyte, which results in a measurable response from an electronic system. The transducer then transforms the product (Kulkarni et al., 2022). Linked changes are converted into amplified, measurable electrical impulses, as illustrated in Figure 1. Furthermore, the transducer's output is processed and presented. At last, the signal can be interpreted as concentration.

Nanotechnology-based methods for rapid disease detection, enhanced fish absorption, vaccinations, hormone-like medicines, and vitamins could completely transform the fisheries and aquaculture industries. While there is a need for increased research and development in applying nanotechnology to aquaculture, several opportunities exist in areas such as fish health management, water treatment within aquaculture, animal breeding, and harvest and post-harvest technology

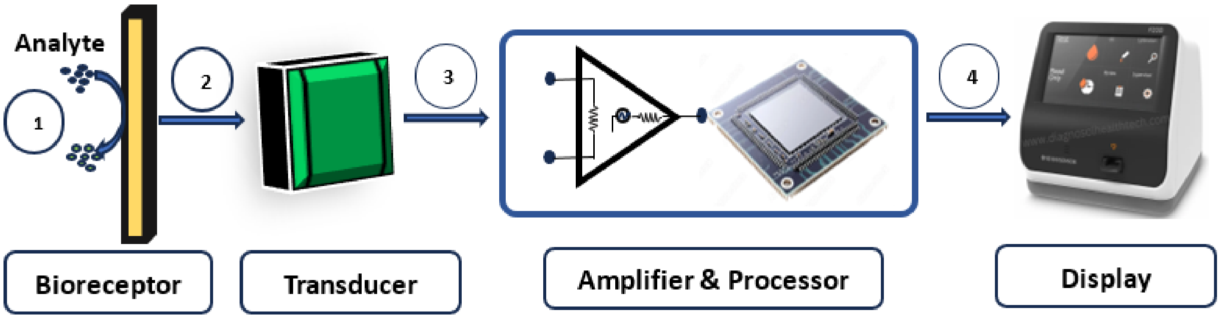

Fig. 1 Schematic diagram and Components of a Nanobiosensor: 1- Biochemical conversion (Bioreceptor, i.e., Antibody, Enzyme, DNA, Bacterial, Cell); 2- Biochemical signal detected by Transducer; 3- Signal sent to Amplifier connected with Processor to modulate and refine; 4- Signals are decoded by Processor and can be shown on Display.

3. Characteristics for an Ideal Nanobiosensor

An ideal nanobiosensor is designed to detect specific substances quickly and accurately while avoiding interference from other materials. It should be extremely small, safe for biological systems, and easy to carry and operate, even outside sophisticated laboratories. The device must be affordable, stable during storage, and capable of delivering reliable and consistent results (Ramesh et al., 2022). Additionally, its performance should remain unaffected by environmental conditions such as temperature, pH, or water quality, ensuring dependable detection with minimal signal disturbance.

4. Types of Nano-biosensors

Nanobiosensors can be categorized by their sensing mechanism and the transducer used to convert biological interactions into measurable signals. Different nanobiosensor platforms employ mechanical, optical, electrical, or nanomaterial-based approaches to detect specific analytes with high sensitivity and accuracy. Such classification helps in understanding their operational principles and selecting suitable sensors for applications including disease diagnosis, environmental monitoring, food safety, and aquaculture management. The major categories of nanobiosensors and their working concepts are illustrated in Figure 2**.**

The principles and major applications of different nanobiosensor systems are summarised in Table 1. The diversity of nanobiosensor platforms demonstrates the versatility of nanotechnology in modern biosensing applications. Variations in sensitivity, response time, portability, and detection mechanisms allow these sensors to be adapted for multiple fields, particularly healthcare diagnostics, environmental surveillance, and precision aquaculture monitoring (Bohara et al., 2024).

5. Application in Aquaculture

Aquaculture is rapidly adopting advanced technologies to improve productivity, fish health, and product quality. Among these innovations, nanobiosensors have emerged as smart monitoring tools capable of providing rapid, accurate, and real-time information throughout the aquaculture production cycle. From pond management to post-harvest processing, these sensors support precision farming and sustainable aquaculture practices.

Table 1 Different Nanobiosensors, principles, and their applications

Sl. No.	Nanobiosensors	Principle	Applications
1.	Mechanical Nanobiosensors	Cantilever bending or resonance change due to mass, stress, or temperature variation	Mass sensing, biomolecule detection, and environmental monitoring

2.	Optical Nanobiosensors	Light resonance or optical signal change upon analyte binding	Biomolecular interaction analysis, diagnostics, biochip sensing
3.	Nanowire Biosensors	Electrical signal modulation using DNA/CNT nanowire hybrids	High-throughput diagnostics, in vivo sensing, and environmental monitoring
4.	Ion Channel Switch Biosensor Technologies	Synthetic membrane generates an electrical signal upon molecular recognition	Detection of proteins, DNA, viruses, drugs, and pesticides
5.	Electronic Nanobiosensors	Electrical bridging between microelectrodes after target DNA binding	Genetic detection, pathogen identification
6.	Nanoshell Biosensors	Spectral change of antibody–nanoshell conjugates in the near-infrared region	Rapid immunoassays, chemical and biomedical sensing
7.	PEBBLE Nanobiosensors	Sensor molecules encapsulated in inert	Intracellular imaging, ion monitoring, and real-time cellular analysis

Smart Monitoring of Soil and Water Quality

Maintaining optimal pond soil and water conditions is essential for healthy fish growth. Nanobiosensors enable continuous monitoring of microbial activity, nutrient levels, pesticides, and toxic metals at extremely low concentrations. By detecting early environmental stress, farmers can take timely corrective measures and prevent disease outbreaks.

Case example: Gold nanoparticle–based aptamer sensors have been successfully used to detect mercury ions (Hg^{2+}) in aquatic environments, while nanowire field-effect transistor biosensors enable ultrasensitive detection of DNA changes associated with environmental stress, thereby supporting real-time water quality assessment (Tu et al., 2018).

Early Detection of Pathogens and Microbes

Disease outbreaks remain one of the biggest challenges in aquaculture. Nanobiosensors can rapidly identify bacteria, viruses, and parasites, even before visible symptoms appear, thereby reducing economic losses. Functionalized nanoparticles and carbon nanotube sensors provide high sensitivity for detecting pathogens directly from water or biological samples.

Case example: Electrical nanowire sensors demonstrated the capability to detect individual virus particles, highlighting their potential for early disease surveillance. Immuno-targeted gold nanoparticles have also been used for the specific detection of bacterial pathogens, such as *Staphylococcus aureus*, in aquatic systems (Rtimi, 2019).

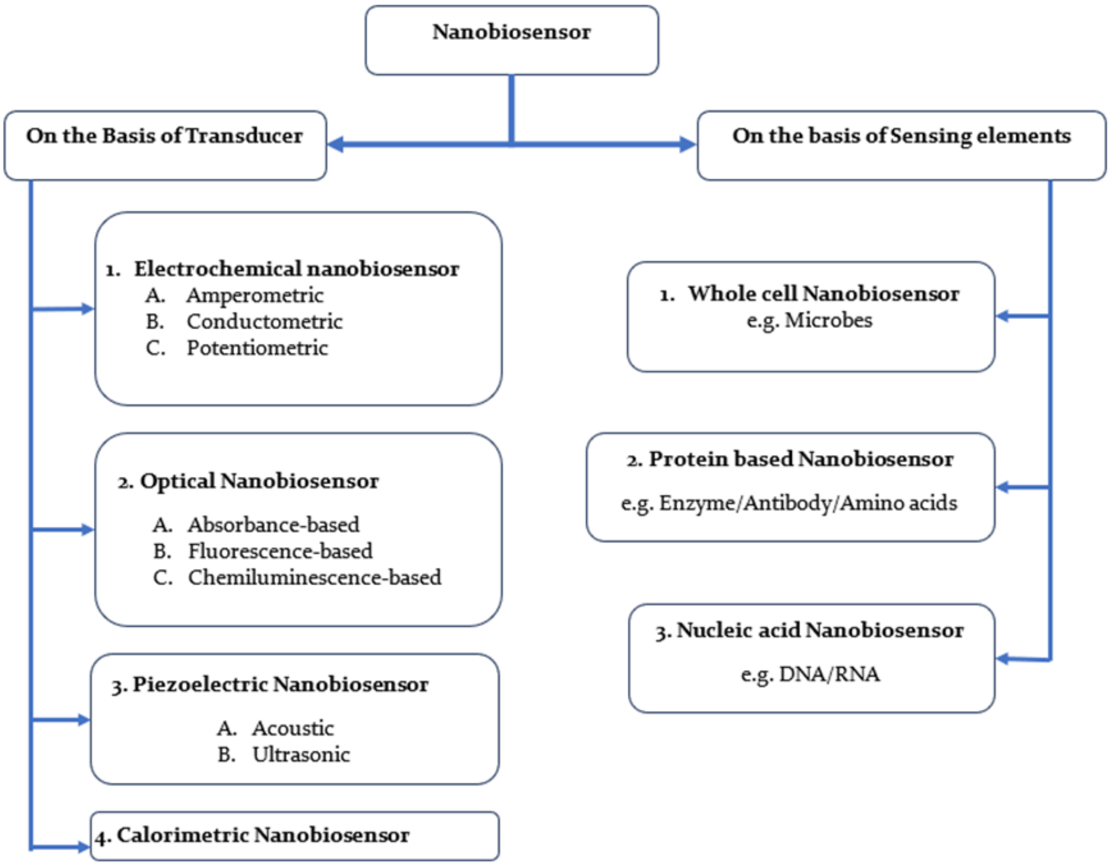

Fig. 2 Types of Nanobiosensor

Fish Tracking and Geolocalization

Modern aquaculture is moving toward intelligent farming systems where individual fish health and behavior can be monitored. Nano-enabled tags and nano-barcode devices, equipped with miniature circuits, enable remote identification and tracking of fish movement, feeding patterns, and physiological status.

Case example: Nano-barcode tagging technology enables automatic scanning and identification of individual fish from a distance, improving stock management, traceability, and smart cage farming operations (Ahuekwe et al., 2023).

Quality Detection in Processed Fish Products

Nanobiosensors also play an important role after harvesting by ensuring seafood safety during storage and transportation. Sensors integrated with DNA-tagged probes can monitor microbial contamination, temperature variations, and package leakage, helping maintain product freshness and consumer safety.

Case example: Nano-barcode systems, combined with color-coded DNA probes, have been used to simultaneously detect pathogens and monitor storage conditions, thereby improving quality control across the seafood supply chain (Rather et al., 2011).

Fish Gender Identification for Breeding Management

Selective breeding programs require accurate identification of fish sex, which is often difficult using external morphology alone. Nanobiosensors based on single-walled carbon nanotubes can detect the hormone 11-ketotestosterone (11-KT), a biomarker associated with male fish development.

Case example: A nanotube-based biosensor successfully measured 11-KT levels in Nile tilapia plasma, showing strong agreement with conventional ELISA analysis (Wu et al., 2022). This technique offers a rapid, non-invasive approach to gender determination and broodstock management.

6. Advantages of Nano-biosensors in Aquaculture

Nanobiosensors provide highly sensitive, rapid detection compared to conventional sensors due to their use of nanostructured materials. They enable real-time monitoring of water quality, environmental stress, and fish health, helping farmers take timely management decisions (Naresh and Lee, 2021). Their portability, accuracy, low cost, and minimal environmental impact improve disease prevention, enhance fish survival, and increase overall aquaculture productivity.

7. Future Prospects

Advancements in nanotechnology are driving the development of smarter, more efficient nanobiosensors. Novel nanomaterials such as gold nanoparticles, carbon nanotubes, magnetic nanoparticles, and quantum dots are improving biomolecule detection, pathogen diagnosis, and environmental monitoring (Bhuma, 2014). Emerging biosensor platforms, including acoustic and optical sensors, are expected to support automated monitoring and precision aquaculture in the future.

8. Conclusion

Nanobiosensors represent a significant technological advancement for fisheries and aquaculture. Their high sensitivity, rapid response, and portability enable efficient monitoring of environmental conditions, disease outbreaks, and fish health. With continued technological progress, nanobiosensors are expected to play a key role in the development of sustainable and intelligent aquaculture systems.

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Bamaniya and Patel (2026)

Otoliths Found from Fish: Their Utilization in the Indian Market

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Abstract

Otoliths are calcareous structures in the inner ear of teleost fishes that function in balance and hearing while also serving as important biological records. This article highlights their morphological and chemical properties and their growing applications in fisheries science, ecological studies, and the Indian market. Species-specific otolith morphology aids in fish identification and stock differentiation, supporting sustainable fisheries management. Chemical signatures, including stable isotopes and elemental composition, provide insights into fish age, migration patterns, habitat use, and environmental history, making them valuable for stock assessment and monitoring environmental change. Beyond scientific applications, otoliths are also used in certain culinary practices in India, reflecting traditional whole-fish utilization and waste reduction, although their nutritional potential remains largely unexplored. Overall, otoliths represent an important multidisciplinary resource with ecological, managerial, and cultural significance in supporting sustainable fisheries and livelihoods.

Keywords: Otoliths, Fisheries, Stock assessment, Fish identification, Stable isotopes

1. Introduction

Otoliths are calcareous structures found in the inner ear of teleost fish and they have received occasions are numerous studies in numerous fields viz. fisheries science, ecology and archaeology. These structures are important to the fish for balance and hearing and constitute useful biological archives capable of revealing life history of fish populations. India: Otolith Utilization beyond Biology, otoliths have an important aspect in terms of biological significance, are also being recognised for their immunological efficiency and potential use in fisheries management, stock assessment, and gastronomic use. Otolith's

Morphological and Chemical Composition, Their Significance in The Indian Market, and Sustainable Fisheries Management are the targeted area.

2. Morphological Characteristics of Otoliths

Important properties of otoliths (e.g., morphology) are species-specific among fish species and can thus be used to identify species and discriminate stocks. For instance, Rani et al. Rani et al 2019 performed a morphometric study on the sagitta otolith of pool barb (*Puntius sophore*) and observed some distinguishing features which could help in identification of species (Rani et al 2019). Morphological analyses such as these are critically important in fisheries management to help inform sustainable practices through proper species identification. In addition, the analysis of otolith shape can also give a better understanding of the ecological niches of its different species, such as shown by (Bani et al., 2013), who studied the comparative morphology of sagittal otolith in some goby species (Bani et al., 2013).

In addition to species identification, otolith morphology can reveal information about the environmental conditions experienced by fish throughout their lives. The chemical composition of otoliths is influenced by factors such as temperature and salinity, which are recorded in the otolith structure as it grows. This property has been utilized in studies to reconstruct the environmental histories of fish populations, as noted by (Disspain et al., 2016), who highlighted the potential of otoliths in archaeological contexts to understand past environmental conditions (Disspain et al., 2016). The ability to link otolith morphology to environmental factors underscores their significance in both ecological research and fisheries management.

3. Chemical Composition and Its Implications

With otolith chemical analysis being one of the most powerful tools to infer movement and population dynamics of fish. Furthermore, the isotope composition of fish otoliths, especially the ratios of given elements, such as oxygen and carbon, provides information on habitats used by fishes during life history stages. For instance, Artetxe-Arrate et al. showed that δ18O values from yellowfin tuna otoliths could be used to trace their origins and movements within the Indian Ocean (Artetxe-Arrate et al., 2021). This information is essential for fisheries management as it enables the characterization of important habitats and the delineation of patterns-of-movement of economically important species.

Moreover, the elemental fingerprints of otoliths can be utilized to assess the health of fish populations and their responses to environmental changes. For instance, Vane et al. (2018) discussed how the organic matrix of otoliths can serve as ontogenetic records, providing insights into resource utilization and environmental adaptations (Vane et al., 2018). This capability is particularly relevant in the context of climate change, where shifts in environmental conditions can significantly impact fish populations. By analyzing otolith chemistry, researchers can monitor these changes and inform management strategies aimed at sustaining fish stocks.

4. Applications in Fisheries Management

The application of otolith in fisheries management is versatile, including age determination, stock evaluation and conservation efforts. Traditionally, otoliths have been used to determine the age of fish, which is important to understand the growth rate and the dynamics of the population. For example, Sardenne et al. (2015) showed that the daily deposition occurs in the otolith of various fish species, which allows for accurate age estimates (Sardenne et al., 2015). This information is necessary to develop effective management strategies that ensure sustainable fishing practices.

In addition to age determination, otoliths are increasingly being utilized for stock assessment. The ability to differentiate between stocks based on otolith morphology and chemistry enables fisheries scientists to make informed decisions regarding catch limits and conservation measures. For example, the research conducted by Artetxe-Arrate et al. (2019) on yellowfin tuna highlights the importance of understanding stock structure for effective management (Artetxe-Arrate et al., 2019). By identifying distinct stocks, fisheries managers can implement targeted conservation strategies that address the specific needs of each population.

Furthermore, the integration of otolith analysis into fisheries management practices has the potential to enhance collaboration among stakeholders, including government agencies, researchers, and the fishing community. As noted by (Carlson et al., 2016), the application of otolith chemistry in fisheries management can bridge the gap between research and practical applications, fostering a more sustainable approach to fishery resources (Carlson et al., 2016). This collaborative effort is essential for addressing the challenges posed by overfishing and environmental changes, ensuring the long-term viability of fish populations.

5. Culinary Uses of Otoliths

In addition to their scientific and management applications, otoliths have found a place in culinary practices, particularly in regions where fish consumption is prevalent. In India, otoliths are sometimes used in traditional dishes, where they are believed to impart unique flavors and textures. The culinary use of otoliths reflects a cultural appreciation for all parts of the fish, promoting sustainability by minimizing waste. This practice aligns with the growing trend of utilizing by-products in food preparation, which is gaining traction in various culinary traditions worldwide.

Moreover, the nutritional value of otoliths is an area that warrants further exploration. While they are primarily composed of calcium carbonate, the potential health benefits associated with their consumption are not well-documented. Future research could investigate the nutritional profiles of otoliths and their potential contributions to dietary health, particularly in regions where fish is a staple food source. This exploration could further enhance the value of otoliths in the Indian market, promoting their use as a sustainable food source.

6. Conclusion

Otoliths represent a valuable resource in the Indian market, with fisheries management, ecological research and spreading applications of culinary practices. Their morphological and chemical features provide insight into fish population dynamics, movements and environmental history. As the demand for permanent fisheries practices increases, the use of otoliths in stock evaluation and management will be rapidly important. In addition, Otolith's culinary capacity highlights the cultural significance of fish and the importance of reducing waste in food production. Constant research and cooperation among stakeholders will be necessary to maximize the benefits of otolith in the Indian market, ensuring sustainability of fish population and livelihood depending on them. Also in India, fish otolith research plays a pivotal role in regulating sustainable fisheries, identifying ancient trade routes, and forecasting monsoon and climate shifts. Indian researchers from premium labs like the ICAR-Central Marine Fisheries Research Institute (CMFRI) and the Centre for Marine Living Resources and Ecology (CMLRE) rely heavily on these structures to manage the country's dense marine and freshwater biomes

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Yadav (2026)

Smart Feed Formulation: Reducing Costs and Increasing Production

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Abstract

Aquaculture is a rapidly growing sector that plays a crucial role in global food security and animal protein production. However, feed accounts for the largest proportion of production costs, making efficient feed management essential for profitability and sustainability. Smart feed formulation involves developing nutritionally balanced and cost-effective diets that meet the specific requirements of cultured species while minimizing waste and environmental impacts. This article highlights the importance of understanding nutrient requirements, selecting appropriate feed ingredients, adopting least-cost formulation techniques, and improving feed conversion efficiency. It also discusses the use of alternative protein sources, feed additives, precision feeding technologies, and on-farm feed production as strategies to reduce feed costs and enhance productivity. Furthermore, emerging innovations such as insect-based proteins, single-cell proteins, and AI-driven feeding systems are explored. Smart feed formulation is fundamental to achieving profitable, sustainable, and environmentally responsible aquaculture production.

Keywords: Aquaculture, Feed Formulation, Feed Conversion Ratio, Precision Feeding, Alternative Feed Ingredients, Sustainability, Fish Nutrition

Introduction

Aquaculture is one of the fastest-growing food production sectors and plays a vital role in global food security by supplying high-quality animal protein. As wild fish catches have stagnated, aquaculture now provides more than half of the aquatic animals consumed worldwide (FAO, 2024). However, feed remains the largest operational expense, accounting for 50–70% of production costs in intensive farming systems. Therefore, efficient nutrition and feed management are essential for improving profitability and fish performance. Fish require balanced diets containing proteins, lipids, carbohydrates, vitamins, and minerals for optimal growth, health, and disease resistance. Traditionally, fish meal and fish oil have been key feed ingredients, but their rising cost and limited availability have increased the need for alternative feed resources. In response, smart feed formulation has emerged as an important strategy for sustainable aquaculture. It involves designing nutritionally balanced and cost-effective diets using nutrient databases, digestibility information, and least-cost formulation techniques. Smart feed formulation improves feed efficiency, reduces production costs, minimizes nutrient waste, and lowers environmental impacts, thereby supporting profitable and sustainable aquaculture development. Feed Strategies focus on balancing nutritional adequacy, ingredient availability, economic efficiency, and environmental sustainability. By accurately matching dietary nutrient levels to the requirements of cultured species, farmers can improve production performance while reducing feed expenses and nutrient waste (Hasan & New, 2009).

Why Feed Formulation Matters

Feed formulation is a key factor in successful aquaculture because nutrition directly affects fish growth, health, survival, reproduction, and farm profitability. Fish require balanced nutrients to support growth, metabolism, immunity, and normal physiological functions. A well-formulated diet improves feed utilization and production efficiency, while poor nutrition can lead to slow growth, disease susceptibility, and economic losses (NRC, 2011).

A balanced fish feed should provide:

Protein: Essential for growth, tissue repair, and enzyme production; it is usually the most expensive feed component (Hardy & Kaushik, 2022).

Lipids (Fats): Provide energy and essential fatty acids needed for growth and reproduction (NRC, 2011).

Carbohydrates: Serve as an economical energy source and help spare protein for growth (Wilson, 1994).

Vitamins and Minerals: Support metabolism, immunity, skeletal development, and physiological functions (NRC, 2011).

Essential Amino Acids and Fatty Acids: Must be supplied through the diet because fish cannot produce them in sufficient quantities (Hardy & Kaushik, 2022).

Feeds that do not meet nutrient requirements can reduce growth, feed efficiency, health, and survival. Conversely, excessive nutrient inclusion increases feed costs and may contribute to environmental pollution through nutrient waste. Therefore, the main objective of feed formulation is to provide the right nutrients in the correct proportions at the lowest possible cost while maximizing fish performance and sustainability (Cho & Bureau, 2001).

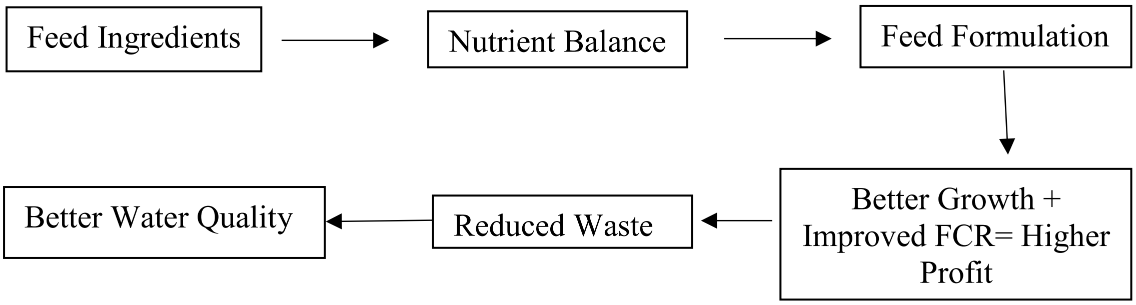

Fig. 1 Importance of feed formulation in aquaculture

Principles of Smart Feed Formulation

Understanding Nutritional Requirements

Different fish species have different nutrient requirements depending on their feeding habits and life stages.

Table 1 Requirement (%) of Nutrients for better growth (NRC, 2011; Hardy & Kaushik, 2022)

Species	**Carp**	**Tilapia**	**Catfish**	**Trout**	**Shrimp**
% of Protein Required	25–35	28–35	28-32	35-50	30-45
% of Lipid Required	5-10	5-10	4-8	15-25	6-10
% of Carbohydrate Required	25-40	25-45	25-40	Less than 20	20-30
% of Vitamin Premix Required	1-2	1-2	1-2	1-2	1-2
% of Mineral Premix Required	1-2	1-2	1-2	1-2	1-2

Juvenile fish generally require higher protein levels than adults because of their rapid growth rates.

Least-Cost Formulation

The objective of modern feed formulation is not to create the cheapest feed but to formulate the least-cost diet that satisfies all nutritional requirements.

This approach uses:

- Nutrient requirement data
- Ingredient composition tables
- Market prices of ingredients

- Linear programming software

The least-cost formulation concept has become a standard tool in commercial feed manufacturing because it minimizes feed costs while maintaining nutritional adequacy.

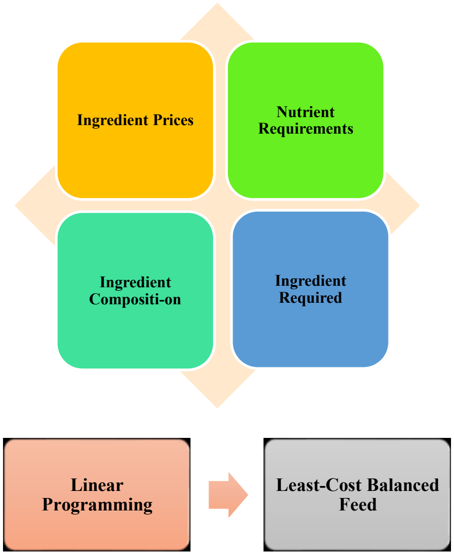

Fig. 2 Least-cost feed formulation approach

Selection of Feed Ingredients

Feed ingredient selection is a critical step in aquaculture feed formulation because it directly influences feed cost, nutrient availability, fish growth, and farm profitability. An ideal ingredient should be nutritious, highly digestible, readily available, cost-effective, and free from contaminants. Since feed represents the largest production expense, careful ingredient selection is essential for developing efficient and economical diets (Hardy & Kaushik, 2022).

Protein Sources

Protein is the most expensive component of aquaculture feeds and is essential for growth, tissue repair, and metabolism. Fish meal has traditionally been the preferred protein source due to its high digestibility and balanced amino acid profile. However, rising costs have increased the use of alternatives such as soybean meal, groundnut cake, mustard oil cake, cottonseed meal, sunflower meal, and insect meal. Soybean meal is widely used because of its high protein content, while black soldier fly larvae meal has emerged as a promising sustainable alternative (Tacon & Metian, 2015; Henry et al., 2015).

Energy Sources

Energy ingredients such as rice bran, wheat bran, maize, broken rice, and cassava meal provide energy for metabolic activities and help spare dietary protein for growth. Maintaining an appropriate energy-to-protein ratio is important for efficient feed utilization and fish performance (NRC, 2011).

Alternative Ingredients for Cost Reduction

To reduce feed costs, aquaculture increasingly utilizes alternative ingredients such as Azolla, duckweed, black soldier fly larvae meal, brewery waste, distillery by-products, and agricultural residues. These materials are often inexpensive, locally available, and can partially replace conventional feed ingredients without compromising fish growth. Their use promotes sustainability, reduces dependence on fish meal, and supports circular economy practices by converting waste products into valuable feed resources (Hasan & New, 2009; Hua, 2021).

Feed Conversion Ratio: The Key to Profitability

Feed Conversion Ratio (FCR) is one of the most important indicators of feed efficiency and farm profitability. It represents the quantity of feed required to produce a unit of fish biomass and is calculated using the following formula:

FCR = Feed Consumed (kg) ÷ Weight Gain (kg)

❖ Relationship Between FCR and Profitability

Lower FCR
↓
Less Feed Required
↓
Reduced Production Cost
↓
Higher Profit Margin

Precision Feeding: Feeding the Right Amount

Effective feeding management is essential for maximizing the benefits of a well-formulated feed. Overfeeding causes feed wastage, poor water quality, and increased disease risks, while underfeeding reduces growth and feed efficiency. Modern aquaculture increasingly uses automatic feeders, sensor-based systems, and AI-assisted technologies to determine optimal feeding rates, reduce waste, and improve feed conversion efficiency, thereby enhancing both profitability and sustainability (Føre et al., 2018).

Role of Feed Additives

Feed additives are widely used to improve growth, feed utilization, and fish health. Probiotics and prebiotics support gut health, enzymes enhance nutrient digestibility, immunostimulants strengthen disease resistance, and organic acids improve nutrient absorption. Although additives may slightly increase feed costs, they often provide greater economic returns through improved growth, survival, and feed efficiency (Dawood et al., 2018).

On-Farm Feed Production

On-farm feed production offers a cost-effective option for small-scale farmers by utilizing locally available ingredients and agricultural by-products. It can reduce feed and transportation costs while increasing resource utilization. However, proper formulation, ingredient quality, mixing, and storage are essential to ensure nutritional adequacy and maintain fish performance (Hasan & New, 2009).

Environmental Benefits of Smart Feed Formulation

Smart feed formulation promotes environmental sustainability by improving nutrient utilization and reducing nitrogen and phosphorus waste released into aquatic ecosystems. The use of alternative protein sources such as plant, microbial, and insect proteins also reduces dependence on fish meal from wild fisheries, supporting sustainable aquaculture development (Cho & Bureau, 2001; Tacon & Metian, 2015).

Future Trends in Feed Formulation

Future advances in aquaculture nutrition focus on improving efficiency, reducing costs, and enhancing sustainability. Promising innovations include insect-based proteins, single-cell proteins from microorganisms, precision nutrition, AI-driven feeding systems, and functional feeds containing probiotics, prebiotics, and other bioactive compounds. These technologies are expected to improve feed efficiency, fish health, and environmental performance while supporting the growing demand for aquatic foods (Henry et al., 2015; Nasseri et al., 2011; Dawood et al., 2018).

Conclusion

Smart feed formulation represents one of the most effective strategies for increasing profitability in aquaculture. By understanding nutritional requirements, selecting cost-effective ingredients, adopting least-cost formulation techniques, improving feed conversion efficiency, and implementing precision feeding practices, fish farmers can significantly reduce production costs and enhance output. As feed continues to account for the largest share of production expenses, the future success of aquaculture will depend on innovative and sustainable feeding strategies. Smart feed formulation not only supports higher production and profitability but also contributes to environmental sustainability and long-term food security.

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Pal and Jha (2026)

Integrated Fish-Crop Farming: A Climate-Smart Pathway for Sustainable Indian Agriculture

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Abstract

Integrated fish–crop farming has emerged as a promising approach for advancing climate-smart and sustainable agriculture in India. By integrating aquaculture with crop production, these systems improve resource use efficiency, nutrient recycling, farm diversification, and livelihood resilience. This article examines integrated fish–crop farming within the Indian agricultural context, highlighting its role in enhancing productivity, ecological sustainability, and climate adaptation. Major Indian models including rice–fish farming, pond-based integrated systems, and emerging aquaponic approaches are discussed, along with regional experiences from Assam, Kerala, and West Bengal. The article also emphasizes the importance of agricultural extension, institutional support, and policy initiatives in promoting adoption and scaling of integrated systems. Although challenges related to technical knowledge, infrastructure, and management remain, integrated fish–crop farming offers significant potential for supporting resilient, diversified, and environmentally sustainable agricultural development in India.

Keywords: Integrated farming systems; Climate-smart agriculture; Aquaculture; Sustainable agriculture

Introduction

Indian agriculture is operating under mounting pressure. Climate variability, shrinking landholdings, rising input costs, natural resource degradation, and unstable farm profitability are reshaping the realities of farming, particularly for smallholder households. Conventional single-enterprise farming systems often struggle to balance productivity, resilience, and livelihood security under these conditions. As a result, diversified, resource-efficient farming approaches are receiving growing attention within climate-smart agriculture debates in India (FAO, 2017; Vaid & Thakkar 2026; APN, 2023). Within this wider transition toward sustainable agriculture, integrated farming systems are emerging as practical alternatives capable of linking multiple farm enterprises into mutually supportive production systems. At the same time, India’s fisheries and aquaculture sector has expanded considerably over the past decade. The country remains one of the world’s leading fish-producing nations, with total fish production increasing from approximately 95.79 lakh tonnes in 2013–14 to nearly 197.75 lakh tonnes during FY 2024-25. The sector contributes substantially to agricultural gross value addition, nutritional security, employment generation, and rural livelihoods (Government of India, 2025; FAO, 2024). Recent policy initiatives, particularly the Pradhan Mantri Matsya Sampada Yojana (PMMSY), have further reinforced the national emphasis on sustainable aquaculture expansion, infrastructure development, technological modernisation, and strengthening the fisheries sector (Government of India, Department of Fisheries, 2025). These parallel developments, agricultural vulnerability on one side and rapid aquaculture growth on the other, create an important opportunity for integrated approaches. In this setting, integrated fish-crop farming emerges not simply as another production model but as a diversification strategy that connects agriculture, aquaculture, climate adaptation, and livelihood resilience within a single farming framework.

Integrated agriculture-aquaculture systems combine crop cultivation with fish production through ecological interactions, nutrient recycling, and efficient resource utilisation. Common models include rice-fish farming, pond-based integrated systems, fish-vegetable cultivation, fish-horticulture integration, and emerging aquaponic approaches. Such systems improve resource use efficiency, diversify production, and support food, nutrition, and livelihood security (Sathoria & Roy, 2022; WorldFish, 2021; WeAdapt, 2021).

Understanding Integrated Fish-Crop Farming

Integrated fish–crop farming is based on a simple principle: farm enterprises function more effectively when biological components interact rather than operate independently. In this approach, fish production is combined with crop cultivation within a connected system designed to improve resource use, nutrient cycling, and farm productivity. Unlike conventional monocropping, where enterprises rely heavily on external inputs and function separately, integrated agriculture–aquaculture systems create ecological linkages in which the outputs of one component support another (FAO, 2017; WeAdapt, 2021). The conceptual framework of integrated fish–crop farming is presented in Figure 1, illustrating the interactions among crop production, fish culture, nutrient flows, and climate-smart farming outcomes.

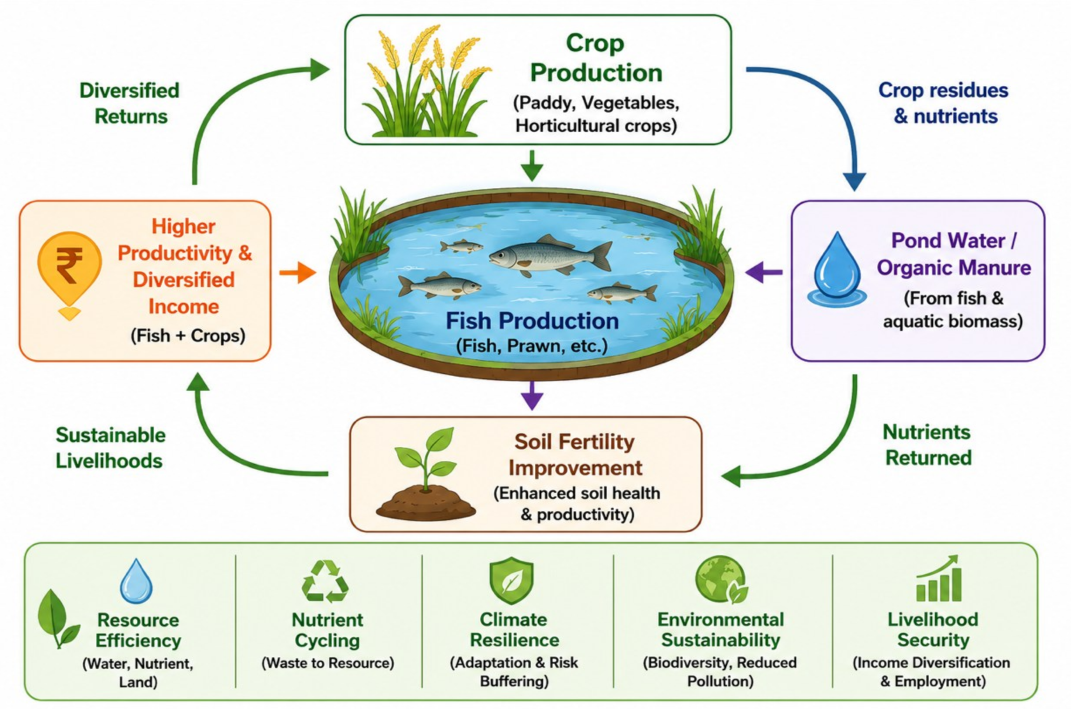
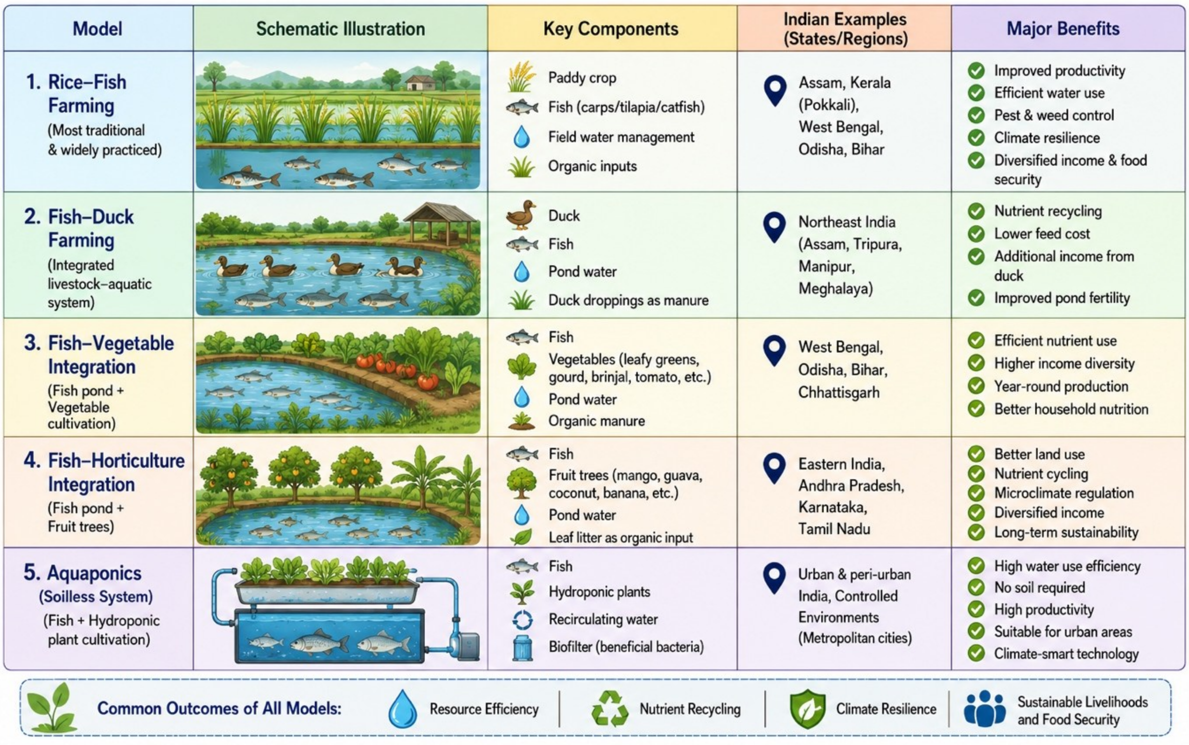


Fig. 1 Integrated fish–crop farming as a climate-smart system

In India, integrated fish–crop farming takes several forms shaped by agro-ecological conditions, water availability, farming traditions, and household livelihood needs. Among these, rice–fish farming remains one of the oldest and most widely documented systems. Fish are reared simultaneously or sequentially within rice fields, creating productive interactions between aquatic and crop components (Sathoria & Roy, 2022). Fish contribute to nutrient cycling, biological pest control, weed regulation, and improved soil–water interactions, while rice fields provide habitat, food resources, and suitable water conditions for aquatic production (WorldFish, 2021).

Beyond rice–fish systems, Indian agriculture supports other forms of integration that broaden production opportunities. Fish–duck farming, practised in parts of Northeast and Eastern India, demonstrates how biological interactions can reduce dependence on external inputs. Duck droppings enrich pond fertility, stimulate natural feed availability, and lower nutrient supplementation requirements, while farmers gain additional returns from duck-based enterprises.

Fish–vegetable and fish–horticulture systems extend integration into surrounding farm spaces. Pond embankments, adjacent land, and nutrient-rich pond resources are used to cultivate vegetables, fruits, and horticultural crops. These arrangements strengthen land use efficiency, encourage nutrient reuse, and support additional farm income (CEEW, 2024; WorldFish, 2021). Pond-based systems frequently build on the same principle by reusing pond water and sediments in crop cultivation, thereby reducing fertilizer dependence and improving internal nutrient cycling. Emerging technologies have added new dimensions to fish–crop integration. Aquaponic systems combine aquaculture and hydroponic cultivation within recirculatory systems where fish waste supplies nutrients for plants. The result is a closed-loop production arrangement characterised by efficient water use, continuous nutrient recovery, and reduced waste generation (CEEW, 2024). The diversity of Indian integrated models and their major functional features is summarized in Figure 2.



Model	Schematic Illustration	Key Components	Indian Examples (States/Regions)	Major Benefits
1. Rice–Fish Farming (Most traditional & widely practiced)		Paddy crop Fish (carps/tilapia/catfish) Field water management Organic inputs	Assam, Kerala (Pokkali), West Bengal, Odisha, Bihar	✓ Improved productivity ✓ Efficient water use ✓ Pest & weed control ✓ Climate resilience ✓ Diversified income & food security
2. Fish–Duck Farming (Integrated livestock–aquatic system)		Duck Fish Pond water Duck droppings as manure	Northeast India (Assam, Tripura, Manipur, Meghalaya)	✓ Nutrient recycling ✓ Lower feed cost ✓ Additional income from duck ✓ Improved pond fertility
3. Fish–Vegetable Integration (Fish pond + Vegetable cultivation)		Fish Vegetables (leafy greens, gourd, brinjal, tomato, etc.) Pond water Organic manure	West Bengal, Odisha, Bihar, Chhattisgarh	✓ Efficient nutrient use ✓ Higher income diversity ✓ Year-round production ✓ Better household nutrition
4. Fish–Horticulture Integration (Fish pond + Fruit trees)		Fish Fruit trees (mango, guava, coconut, banana, etc.) Pond water Leaf litter as organic input	Eastern India, Andhra Pradesh, Karnataka, Tamil Nadu	✓ Better land use ✓ Nutrient cycling ✓ Microclimate regulation ✓ Diversified income ✓ Long-term sustainability
5. Aquaponics (Soilless System) (Fish + Hydroponic plant cultivation)		Fish Hydroponic plants Recirculating water Biofilter (beneficial bacteria)	Urban & peri-urban India, Controlled Environments (Metropolitan cities)	✓ High water efficiency ✓ No soil required ✓ High productivity ✓ Suitable for urban areas ✓ Climate-smart technology

Common Outcomes of All Models: Resource Efficiency | Nutrient Recycling | Climate Resilience | Sustainable Livelihoods and Food Security

Fig. 2 Major integrated fish–crop farming models practiced in India

Integrated farming systems are increasingly recognised as resource-efficient and climate-responsive agricultural approaches. Diversification across fisheries and crop enterprises can reduce production risks, stabilise farm income, optimise water and nutrient use, and strengthen food and nutritional security, particularly among smallholder households (Vaid & Thakkar 2026; WorldFish, 2021). Studies on ecological rice–fish systems have also reported gains in biodiversity conservation, ecological intensification, and long-term resource sustainability through enhanced nutrient flows and lower dependence on chemical inputs (Xie et al., 2011). Given India's large smallholder population, diverse agro-climatic conditions, and growing emphasis on sustainable intensification, integrated fish–crop farming offers a practical approach for connecting agricultural production, ecological sustainability, and livelihood support within the same farming system.

Integrated Fish–Crop Farming as a Climate-Smart Pathway for Sustainable Agriculture

Integrated fish–crop farming is increasingly gaining relevance within climate-smart agriculture discussions as farming systems face rising climatic uncertainty, production costs, and resource pressures (WorldFish, 2021). The approach aligns closely with the objectives of climate-smart agriculture, which emphasises productivity enhancement, adaptive capacity, and environmental sustainability under changing climatic conditions (FAO, 2017). Rather than treating fisheries and crop production as separate activities, integrated fish–crop farming connects them through shared flows of water, nutrients, biological interactions, and farm resources. As illustrated earlier in Figure 1, the effectiveness of the system lies in its ecological connectivity.

A major advantage of integrated fish-crop farming is its ability to improve resource use within the farm system. Nutrients, crop residues, water, and biological resources are reused rather than functioning as isolated or wasted inputs. In rice–fish systems, fish activity contributes to nutrient cycling, biological pest regulation, and improved soil–water interactions. Likewise, pond-based systems reuse nutrient-rich pond water and sediments in crop cultivation, reducing dependence on external fertilizers and improving input efficiency (Sathoria & Roy, 2022; WorldFish, 2021). For Indian farmers dealing with rising input costs and resource constraints, such internal recycling carries both ecological and economic value.

Climate resilience forms another important dimension of integrated systems. Indian agriculture increasingly faces rainfall irregularities, droughts, floods, heat stress, and fluctuating production conditions. Under these circumstances, dependence on a single enterprise can increase livelihood vulnerability. Integrated fish–crop farming addresses this challenge through production diversification. By combining fisheries with crop cultivation, households create multiple production streams capable of buffering climatic and market shocks. Income diversification and production flexibility make these systems particularly relevant for smallholder farming environments characterised by uncertainty and constrained resources.

The environmental contribution of integrated systems is equally significant. Climate-smart agriculture places growing emphasis on ecological intensification, reduced external input dependence, and sustainable resource management. Integrated fish–crop systems support these objectives through nutrient recycling, biological regulation, reduced waste generation, and improved ecosystem functioning. Studies on ecological rice–fish systems have reported gains in biodiversity conservation, improved nutrient flows, and reduced chemical dependence, highlighting the sustainability potential of integrated agriculture–aquaculture systems (Xie et al., 2011). The practical implications of these systems for farming households are summarized in Table 1.

Table 1. Why integrated fish–crop farming matters for Indian farmers

Dimension	Practical relevance
Diversified income	Multiple production streams reduce dependence on a single enterprise
Nutrient recycling	Improved internal input efficiency through ecological reuse
Reduced production cost	Lower fertilizer, nutrient, and supplementary feed dependence
Climate resilience	Improved buffering against climatic and market shocks
Employment generation	Expanded year-round livelihood and farm activity opportunities

Within the Indian context, integrated fish–crop farming represents more than a sustainability concept. It offers a practical approach for improving productivity, strengthening adaptive capacity, and supporting resilient agricultural livelihoods.

Indian Models and Success Experiences of Integrated Fish–Crop Farming

India's agro-ecological diversity has created favourable conditions for multiple forms of integrated fish–crop farming. Rather than representing a single standardised model, these systems adapt to local ecology, water availability, and livelihood requirements. The diversity of Indian integrated farming approaches was introduced earlier in Figure 2; selected regional experiences further illustrate how these systems operate under field conditions.

Rice–fish farming occupies a central place within India's integrated agriculture–aquaculture landscape. Practised across states such as Assam, West Bengal, Odisha, Kerala, and other parts of Eastern India, rice–fish systems combine paddy cultivation with fish production to improve land use, diversify household production, and strengthen farm sustainability (Sathoria & Roy, 2022).

Assam provides an important example of climate-responsive rice–fish integration within water-rich and flood-affected farming environments. Integrated systems in the state make productive use of seasonal water resources while reducing dependence on single-enterprise agriculture. Farmers benefit from simultaneous crop and aquatic production, improved livelihood diversification, and greater adaptive capacity under climatic uncertainty

(NITI Aayog, 2025). A representative example of Indian rice-fish integration is shown in Plate 1.

Plate 1. Rice–fish farming system in India

Another widely recognised example is Kerala's Pokkali paddy–fish system, a traditional production practice adapted to saline coastal wetlands. The system combines salt-tolerant paddy cultivation with seasonal fish or shrimp production, creating a model of ecological adaptation, biodiversity conservation, and livelihood generation. Its continued relevance illustrates how traditional farming knowledge can align with contemporary climate-smart agriculture discussions.

Integrated systems in India extend beyond rice-based landscapes. In parts of Northeast India, fish-duck farming demonstrates how biological interactions can be translated into practical farm management advantages. Ducks raised around ponds contribute organic manure directly to aquatic systems, improving pond fertility and stimulating natural productivity. Farmers derive returns from fish, duck, and sometimes crop enterprises, making the system particularly suitable for diversified smallholder livelihoods. The operational structure of integrated fish-duck farming is illustrated in Plate 2.

Plate 2. Integrated fish–duck farming system

West Bengal and several parts of Eastern India provide strong examples of pond-based integrated farming. Fish production is frequently combined with vegetables, horticultural crops, or mixed agricultural enterprises organised around efficient use of water and nutrient resources. Farmers often cultivate vegetables on pond bunds using nutrient-rich pond water and sediments, reducing fertilizer dependence while generating complementary crop income (Sathoria & Roy, 2022; WorldFish, 2021)

In Odisha, rice-based integrated systems incorporating fisheries components are increasingly discussed as climate-responsive approaches capable of improving productivity, resource use, and livelihood diversification under variable environmental conditions (ICAR-NRRI, 2024).

Alongside traditional systems, India is also witnessing growing interest in emerging integrated technologies. Aquaponics, biofloc-supported crop integration, and other resource-efficient aquaculture models are increasingly entering discussions on sustainable food production, urban agriculture, and climate-smart innovation. By linking aquaculture with hydroponic cultivation or recirculatory nutrient systems, these approaches extend integrated farming concepts into more technologically intensive production environments.

Taken together, these examples highlight the breadth of integrated fish–crop farming in India. Across traditional, pond-based, and emerging systems, the underlying emphasis remains the same: improving resource use, expanding livelihood options, and adapting agricultural production to diverse farming realities.

Role of Agricultural Extension and Policy Support in Promoting Integrated Fish–Crop Farming

The long-term success of integrated fish–crop farming depends on more than technical feasibility. Adoption is shaped by access to knowledge, training, institutional support, financial incentives, and advisory systems. Because integrated farming combines multiple enterprises within a single production system, farmers often require practical guidance, confidence-building support, and locally relevant technical knowledge during the transition process.

Agricultural extension therefore plays a central role in promoting integrated systems. From an extension perspective, integrated fish–crop farming involves behavioural, managerial, and institutional adaptation rather than simple technology transfer. Participatory approaches such as on-farm demonstrations, farmer field schools, experiential learning programmes, and peer-to-peer knowledge exchange can strengthen farmer understanding and confidence in integrated systems (MANAGE, 2023; APN, 2023). The extension pathway supporting adoption and scaling of integrated fish–crop farming in India is presented in Figure 3.

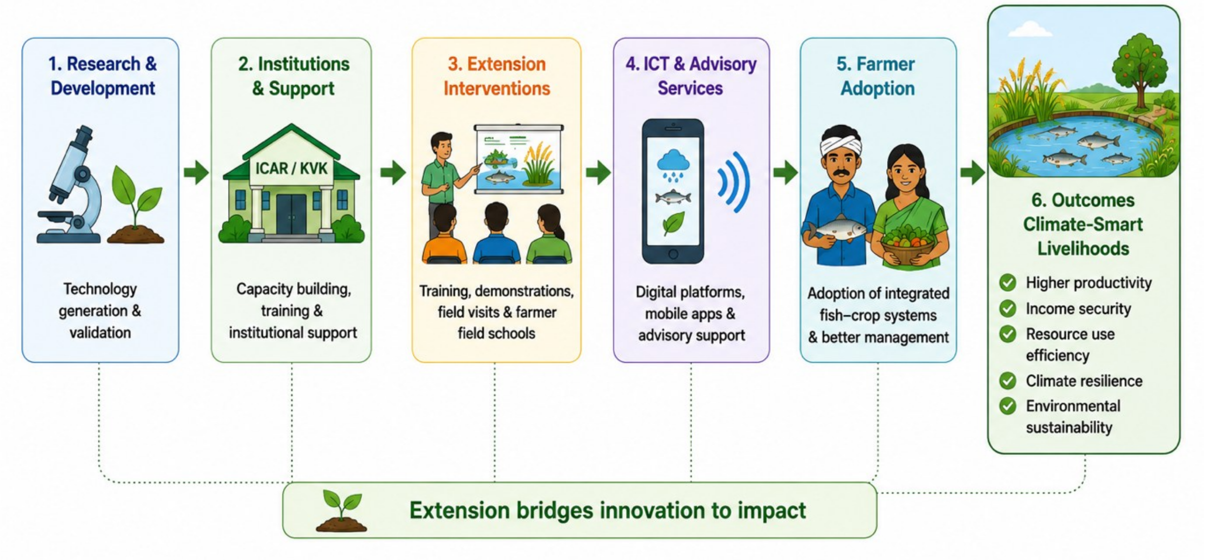


Fig. 3 Role of agricultural extension in scaling integrated fish–crop farming

Several institutions in India already provide an enabling foundation for integrated agriculture–aquaculture development. Organisations such as the Indian Council of Agricultural Research (ICAR), ICAR–Central Institute of Freshwater Aquaculture (ICAR-CIFA), Krishi Vigyan Kendras (KVKs), state fisheries departments, and agricultural universities contribute through research, technical advisories, farmer training, demonstrations, and capacity-building programmes. Their role is particularly important in integrated systems where management practices must be adapted to local agro-ecological and production conditions.

Demonstration-based learning remains especially valuable. Farmers are often more willing to adopt integrated systems when they observe practical field outcomes under conditions similar to their own production environments. KVK demonstrations, community learning platforms, farmer-to-farmer interactions, and adaptive field trials can therefore help reduce uncertainty around integrated fish–crop technologies.

The extension landscape is also evolving. ICT-enabled advisory services, mobile-based climate information systems, digital learning tools, online technical advisories, and farmer collectivisation platforms such as Farmer Producer Organizations (FPOs) are expanding opportunities for knowledge dissemination and coordinated adoption among farming communities (MANAGE, 2023; ICAR-CIFA, 2024).

Policy support represents another important component of integrated farming promotion. National initiatives such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY) have strengthened attention toward fisheries modernisation, sustainable aquaculture development, infrastructure enhancement, entrepreneurship promotion, and capacity building in India (Government of India, 2025). Although not designed exclusively for fish–crop integration, these initiatives create enabling conditions through financial assistance, institutional support, skill development, and improved access to inputs and markets.

Challenges and Future Opportunities

Despite its potential, integrated fish–crop farming faces challenges related to technical knowledge, infrastructure, investment requirements, fragmented advisory delivery, and uneven access to extension services. Small landholdings, water constraints, and environmental uncertainties such as floods, droughts, and salinity can further influence adoption. However, innovations including aquaponics, Biofloc systems, precision aquaculture, and climate-smart technologies offer promising opportunities. Wider scaling will require stronger research, institutional convergence, farmer-centred extension, and supportive policy environments that translate integrated farming concepts into practical solutions for Indian farmers.

Conclusion

Integrated fish-crop farming represents more than an alternative production practice; it offers a practical climate-smart pathway for addressing the interconnected challenges of productivity, resource degradation, livelihood insecurity, and climate uncertainty in Indian agriculture. Experiences from rice-fish, fish-duck, pond-based, and emerging integrated systems demonstrate their potential to strengthen resource efficiency, diversification, and ecological resilience. However, wider adoption will depend on stronger research, participatory extension, institutional convergence, and supportive policy frameworks capable of translating integrated farming concepts into scalable, farmer-centred solutions across diverse Indian agro-ecological contexts.

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Understanding Milk Composition for Better Dairy Farming

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Abstract

Milk is a highly nutritious food that plays an important role in human health and the global dairy industry. It contains essential nutrients such as water, fat, proteins, lactose, minerals, and vitamins, which contribute to its nutritional and economic value. Understanding milk composition is essential for dairy farmers as it directly influences milk quality, processing efficiency, and farm profitability. The composition of milk varies due to factors such as breed, nutrition, stage of lactation, animal health, and environmental conditions. Higher levels of milk fat and protein improve the yield and quality of dairy products such as butter, cheese, paneer, and yogurt. Proper feeding, health management, and genetic improvement can enhance milk composition and productivity. Modern technologies, including precision nutrition and digital herd management, further support the production of high-quality milk and sustainable dairy farming.

Keywords: Milk Composition, Dairy Farming, Milk Quality, Dairy Nutrition, Farm Profitability

Introduction

Milk is one of the most important agricultural commodities worldwide and is widely recognized as a complete and highly nutritious food because it provides a balanced combination of proteins, fats, carbohydrates, vitamins, and minerals essential for human health (FAO, 2013; Fox et al., 2015). The dairy sector contributes significantly to global food security, nutritional well-being, rural development, and agricultural economies. In many developing countries, dairy farming serves as an important source of income, employment, and livelihood support for millions of smallholder farmers (FAO, 2013). For dairy producers, milk is not merely a food product but a valuable economic commodity whose quality directly influences market returns and farm profitability.

Understanding milk composition is essential for efficient dairy farm management because the quantity and quality of milk are determined by its various chemical constituents. Milk composition refers to the relative proportions of water, fat, proteins, lactose, minerals, vitamins, enzymes, and other bioactive compounds present in milk (Walstra et al., 2006). These components collectively determine the nutritional value, processing characteristics, shelf life, and commercial value of milk and dairy products. Knowledge of milk composition enables farmers to make informed decisions regarding feeding strategies, breeding programs, health management, and milk quality improvement practices, ultimately enhancing dairy farm productivity and profitability (Fox et al., 2015).

What is Milk?

Milk is a natural biological secretion produced by the mammary glands of mammals following parturition, with the primary purpose of providing complete nourishment to newborn offspring during the early stages of life (Fox et al., 2015). It contains all the essential nutrients required for growth and development, including proteins, fats, carbohydrates, vitamins, minerals, and water. Because of its balanced nutritional composition and high digestibility, milk is often referred to as “nature's perfect food” (Walstra et al., 2006).

The composition of milk is not constant and can vary considerably depending on several factors, including animal species, breed, stage of lactation, age, nutritional status, health condition, season, environmental temperature, and management practices (NRC, 2021). For example, buffalo milk generally contains higher fat and total solids than cow milk, while colostrum produced immediately after calving contains substantially higher concentrations of proteins and antibodies than normal milk (ICAR, 2023). Understanding these variations is important for dairy farmers because they influence milk quality, processing suitability, and economic value.

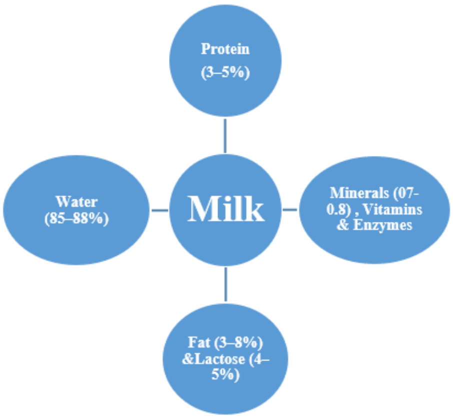

Fig. 1 Major components of milk

1. Water

Water is the largest component of milk, accounting for about 85–88% of its composition and serving as the medium for other milk constituents such as proteins, lactose, minerals, and vitamins (Walstra et al., 2006; Fox et al., 2015). It maintains the fluid nature of milk and facilitates nutrient transport (Fox et al., 2015). Adequate water intake is essential for digestion, metabolism, thermoregulation, and milk production in dairy animals (NRC, 2021). Water consumption is closely associated with feed intake and milk yield, making access to clean drinking water a critical management practice (NRC, 2021). During heat stress, additional water is required to regulate body temperature and sustain production (Beede, 2012). High-producing dairy cows may consume 60–120 liters of water daily, depending on environmental and production conditions (NRC, 2021; Beede, 2012). Therefore, an adequate supply of clean water is essential for maintaining milk yield, milk quality, and animal health (NRC, 2021).

2. Milk Fat

Milk fat is one of the most important components of milk, contributing significantly to its nutritional value, flavor, texture, and processing quality (Fox et al., 2015; Walstra et al., 2006). It is present as tiny fat globules and serves as a concentrated source of energy for both humans and animals (Jensen, 2002). The fat content varies among species, with cow milk containing about 3.5–5.0% fat and buffalo milk containing 6.5–8.0%, making buffalo milk particularly suitable for products such as butter, ghee, and paneer (ICAR, 2023). Milk fat enhances the taste, aroma, creaminess, and overall acceptability of dairy products (Walstra et al., 2006). It also supplies essential fatty acids and acts as a carrier for fat-soluble vitamins A, D, E, and K (Fox et al., 2015). Because milk fat greatly influences product quality and market value, it is often used as a basis for milk pricing, directly affecting dairy farm profitability (ICAR, 2023).

Table 1 Fat content (%) of milk from different animal species (Walstra et al., 2006)

Species	Fat (%)
Cow	3.5–5.0
Buffalo	6.5–8.0
Goat	3.0–4.5
Sheep	6.0–8.0

3. Milk Proteins

Milk proteins are highly nutritious components that constitute approximately 3–5% of milk and provide all essential amino acids required for human growth and development (Fox et al., 2015; Walstra et al., 2006). They play a vital role in the manufacture of dairy products such as cheese, paneer, yogurt, and other fermented products (Fox et al., 2015). Milk proteins are broadly classified into casein (about 80%) and whey proteins (about 20%). Casein is the major protein responsible for curd formation and is rich in amino acids, calcium, and phosphorus, making it important for growth and bone development (Walstra et al., 2006; Fox et al., 2015). Whey proteins remain in the liquid portion after coagulation and include β-lactoglobulin, α-lactalbumin, immunoglobulins, and lactoferrin. These proteins are highly digestible and possess antioxidant, antimicrobial, and immune-supporting properties (Haug et al., 2007; Korhonen & Pihlanto, 2006). Adequate dietary protein intake improves milk protein synthesis and overall milk quality (NRC, 2021).

4. Lactose

Lactose is the principal carbohydrate in milk and accounts for approximately 4–5% of its composition (Walstra et al., 2006). It is a disaccharide made up of glucose and galactose and is synthesized exclusively in the mammary gland (Fox et al., 2015). Lactose plays an important role in regulating milk volume by controlling the osmotic movement of water into milk secretions (Fox et al., 2015). It serves as a major source of energy, particularly for infants, and contributes significantly to the nutritional value of milk (FAO, 2013). Lactose also enhances the absorption of minerals such as calcium and phosphorus, supporting bone growth and development (FAO, 2013). Additionally, it promotes the growth of beneficial intestinal bacteria, improving gut health and digestion (Fox et al., 2015). Since lactose concentration remains relatively stable, it is often used as an indicator of udder health. Reduced lactose levels may indicate mastitis or other mammary gland disorders (Harmon, 1994).

5. Minerals

Milk is an excellent source of essential minerals required for growth, metabolism, enzyme activity, nerve transmission, and maintenance of physiological balance (Walstra et al., 2006). Important minerals present in milk include calcium, phosphorus, potassium, magnesium, and sodium. Calcium and phosphorus are particularly important because they contribute to the development and maintenance of strong bones and teeth (FAO, 2013). Milk is widely regarded as one of the best natural dietary sources of these minerals due to their high bioavailability and balanced ratio (Fox et al., 2015). Potassium helps maintain fluid and electrolyte balance, magnesium supports enzyme activation and muscle function, while sodium plays a key role in nerve impulse transmission and fluid regulation (Walstra et al., 2006). These minerals significantly enhance the nutritional value of milk and support overall health.

6. Vitamins

Milk naturally contains a variety of fat-soluble and water-soluble vitamins that support growth, immunity, metabolism, and overall well-being (Walstra et al., 2006). Important vitamins found in milk include vitamins A, D, E, K, B_2 (riboflavin), and B_{12}. Vitamin A promotes vision, immunity, and normal growth, while vitamin D enhances calcium absorption and bone development (FAO, 2013). Vitamin E functions as an antioxidant that protects cells from oxidative damage, and vitamin K is essential for blood clotting (Fox et al., 2015). Among the water-soluble vitamins, riboflavin and vitamin B_{12} play important roles in energy metabolism and red blood cell formation (Fox et al., 2015). Together, these vitamins improve the nutritional quality of milk and contribute to human health.

Factors Affecting Milk Composition

Milk composition is influenced by a combination of genetic, nutritional, physiological, health, and environmental factors (NRC, 2021).

Breed

Genetic factors play a major role in determining milk composition. Different breeds produce milk with varying concentrations of fat, protein, and total solids.

Table 2 Major minerals present in milk and their functions (FAO, 2013; Walstra et al., 2006; Fox et al., 2015)

Breed	Fat (%)	Protein (%)
Holstein Friesian	3.5–4.0	3.0–3.3
Jersey	4.8–5.5	3.7–4.0
Murrah Buffalo	7.0–8.0	4.0–4.5

Nutrition

Balanced feeding has a direct influence on milk yield and composition. Adequate energy, protein, minerals, vitamins, and fiber are essential for maintaining optimum milk fat and protein percentages (NRC, 2021).

Stage of Lactation

Milk composition changes throughout the lactation cycle. Colostrum produced immediately after calving contains exceptionally high concentrations of proteins, immunoglobulins, vitamins, and minerals that provide passive immunity to newborn calves (Godden, 2008). Milk fat percentage often increases during late lactation as milk yield declines.

Animal Health

Animal health significantly affects milk quality. Diseases such as mastitis can reduce milk fat, protein, and lactose concentrations while increasing somatic cell counts and negatively affecting processing quality (Harmon, 1994).

Environmental Conditions

Environmental factors such as temperature, humidity, season, housing conditions, and heat stress can influence feed intake, metabolism, milk yield, and milk composition. Heat stress is particularly known to reduce milk fat and protein content in dairy animals (West, 2003).

Importance of Milk Composition in Dairy Farming

Milk composition is important because it determines the nutritional quality, processing value, and market price of milk. Components such as fat, protein, and solids-not-fat (SNF) directly affect dairy farmers' income. Milk with higher fat and protein content is preferred for producing butter, ghee, cheese, paneer, and yogurt due to its higher yield and better quality. Changes in milk composition can also indicate health and nutritional problems in dairy animals, helping farmers take timely corrective measures. Therefore, maintaining good milk composition improves milk quality, animal health, and farm profitability.

Future Trends in Dairy Nutrition and Milk Quality

Modern dairy farming is increasingly using precision nutrition, genomic selection, and automated milking technologies to improve milk quality and production efficiency. Advanced feed additives such as probiotics, bypass proteins, and protected fats help enhance nutrient utilization and milk composition. Technologies including artificial intelligence, sensors, and digital herd management systems enable better monitoring of animal health and milk quality. These innovations are expected to improve productivity, sustainability, and profitability in the dairy sector.

Conclusion

Milk composition is an important indicator of dairy animal productivity, health, nutritional status, and milk quality. The major components of milk—water, fat, protein, lactose, minerals, and vitamins—determine its nutritional and economic value. These components are influenced by factors such as breed, feeding practices, stage of lactation, health status, and environmental conditions. Therefore, understanding milk composition is essential for effective dairy management and quality milk production. Knowledge of milk composition helps farmers improve feeding strategies, maintain animal health, enhance processing efficiency, and increase profitability. Higher fat and protein content improves the value of milk and dairy products such as butter, ghee, cheese, paneer, and yogurt. In addition, regular monitoring of milk composition can help identify nutritional and health-related problems at an early stage.

With advancements in precision nutrition, genetic improvement, and modern dairy technologies, maintaining optimum milk composition will become increasingly important. Adopting scientific management practices can improve milk quality, animal welfare, and farm income. Thus, a sound understanding of milk composition forms the foundation of sustainable, efficient, and profitable dairy farming.

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Ensuring Stable Tomato Prices in India: Challenges and Solutions

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Abstract

Tomato is one of the most widely cultivated vegetable crops in India and plays a crucial role in food security, nutrition, and farmer livelihoods. Despite increasing production, tomato farmers frequently face severe price crashes during harvest seasons, while consumers often experience sharp price increases during periods of shortage. This apparent contradiction, commonly known as the tomato price paradox, reflects the complex interaction between production, perishability, storage limitations, market arrivals, and supply chain inefficiencies. Seasonal gluts, weather extremes, inadequate processing facilities, and poor market intelligence contribute significantly to price volatility. This article explores the major factors responsible for tomato price fluctuations in India, their impact on farmers and consumers, and practical strategies to improve market stability. Strengthening storage infrastructure, promoting farmer producer organizations, expanding processing industries, and improving market forecasting systems can help create a more resilient tomato value chain that benefits both producers and consumers.

Keywords: Tomato, Price Volatility, Agricultural Marketing, Farmers, Supply Chain, Market Intelligence

Introduction: The Vegetable That Keeps Making Headlines

Few agricultural commodities receive as much public attention in India as tomatoes. Almost every year, newspapers and television channels report either farmers throwing tomatoes on roads due to extremely low prices or consumers struggling to purchase tomatoes because of unprecedented price increases. In some years, farmers receive less than ₹5 per kilogram during peak harvest periods, while retail prices in urban markets may exceed ₹100 per kilogram during supply shortages. This recurring phenomenon raises an important question: why do tomato prices fluctuate so dramatically? More importantly, why do farmers suffer from low prices when production is high, while consumers pay exceptionally high prices when production declines?

Tomato is not merely a vegetable crop; it is an important source of income for thousands of farming households across India. It is cultivated in almost all states and forms an essential component of Indian diets. However, the economic realities surrounding tomato cultivation often expose farmers to substantial risks. The frequent mismatch between production and prices highlights structural weaknesses in agricultural marketing systems. Understanding the reasons behind these fluctuations is essential for developing sustainable solutions that can protect both producers and consumers.

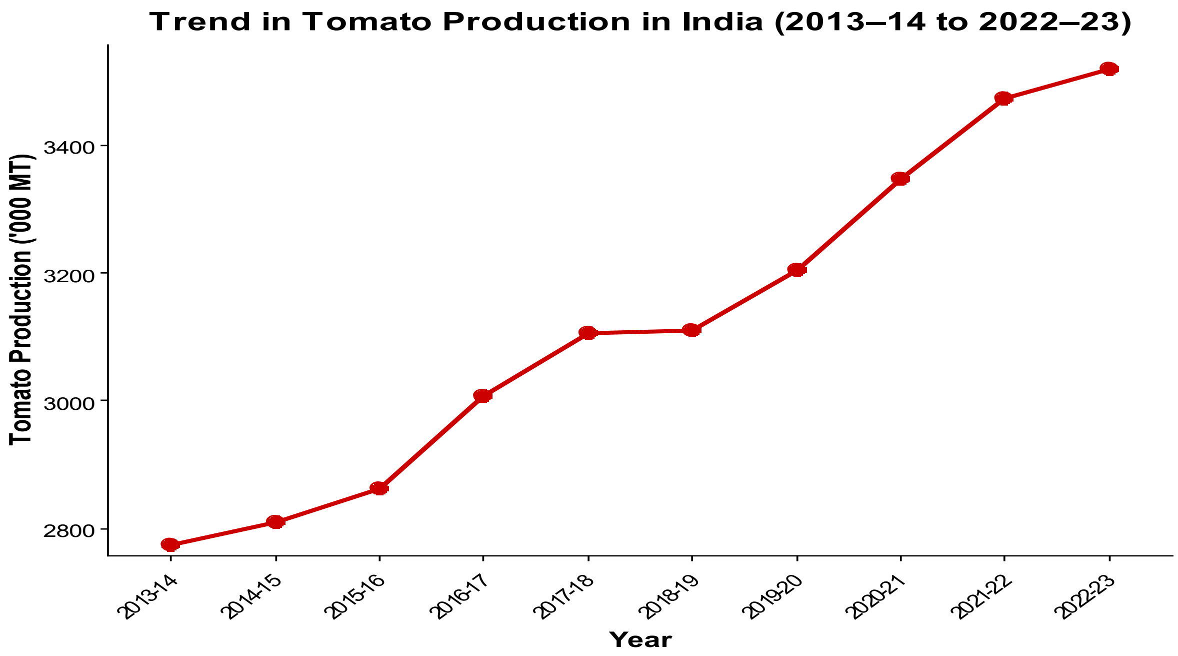

Fig. 1 Representation of Trend in Production of Tomato over the years (Source: National Horticulture Board, 2023)

India's Tomato Economy

India is among the world's leading producers of tomatoes. Major tomato-producing states include Andhra Pradesh, Madhya Pradesh, Karnataka, Gujarat, Odisha, Maharashtra, and Telangana. Figure 1 above illustrates the increasing trend of tomato in India over the years. The crop occupies a significant share of the vegetable sector and contributes substantially to rural employment generation. Tomatoes are cultivated throughout the year under different agro-climatic conditions. Their widespread use in households, hotels, food processing industries, and institutional kitchens ensures continuous demand. The crop also provides relatively quick returns compared to many field crops, making it attractive for small and marginal farmers. However, tomato cultivation is characterized by high production risks and considerable market uncertainty. Unlike cereals, tomatoes are highly perishable and cannot be stored for long periods without proper infrastructure. Consequently, farmers often become vulnerable to market fluctuations immediately after harvest.

Why Do Tomato Prices Crash?

Seasonal Gluts and Excess Market Arrivals

One of the primary reasons for tomato price crashes is the occurrence of seasonal gluts. Favorable weather conditions, attractive prices during previous seasons, and increased cultivation area often encourage farmers to expand tomato production. When many farmers harvest simultaneously, markets receive large quantities of tomatoes within a short period. As supply increases rapidly, market prices decline. Since tomatoes cannot be stored for extended periods under normal conditions, farmers are compelled to sell immediately. This excess supply frequently results in distress sales and substantial financial losses.

Andhra Pradesh is one of India's leading tomato-producing states and frequently experiences sharp price fluctuations. Markets such as Madanapalle in Chittoor district often witness large arrivals during peak harvesting periods. When supply exceeds demand, wholesale prices may decline substantially, reducing farmers' profitability despite good production levels.

Perishability: The Biggest Challenge

Tomato is among the most perishable agricultural commodities. After harvest, quality deterioration begins rapidly, particularly under high temperatures. Farmers must sell their produce quickly to avoid spoilage. Unlike grains, which can be stored for months, tomatoes often have only a limited marketing window. This reduces farmers' bargaining power and strengthens the position of intermediaries and traders during periods of oversupply.

Inadequate Storage Infrastructure

Cold storage and refrigerated transportation facilities remain insufficient in many tomato-producing regions. The absence of efficient cold chains forces farmers to dispose of produce immediately after harvest. Investment in modern storage infrastructure could help distribute market arrivals over time and reduce the severity of price crashes.

Limited Processing Capacity

Tomatoes can be converted into value-added products such as puree, ketchup, paste, sauces, and dehydrated products. However, only a relatively small proportion of India's tomato production is processed. A stronger processing sector could absorb surplus production during bumper harvests and provide an alternative market outlet for farmers. Unfortunately, inadequate processing infrastructure limits this opportunity.

Why Do Tomato Prices Suddenly Rise?

While farmers often suffer from low prices during periods of surplus production, consumers experience the opposite problem when supplies become scarce.

Weather Extremes

Tomato cultivation is highly sensitive to weather conditions. Excessive rainfall, floods, droughts, heat waves, and unseasonal weather can damage crops and reduce market arrivals. Recent years have demonstrated how climate-related disruptions can rapidly influence tomato prices. Heavy rainfall and heat stress have repeatedly affected production in major tomato-growing regions, contributing to supply shortages and price spikes.

Pest and Disease Incidence

Tomato crops are vulnerable to various pests and diseases, including fruit borers, leaf curl virus, and fungal infections. Severe outbreaks can reduce both yield and quality, limiting the quantity of marketable produce.

Transportation and Supply Chain Disruptions

Efficient transportation plays a crucial role in maintaining stable vegetable supplies. Disruptions in logistics, rising fuel costs, road blockages, or adverse weather conditions can affect the movement of tomatoes from production centres to consumption markets. Even temporary disruptions may create local shortages and trigger sharp increases in retail prices.

Karnataka's Kolar market, one of the largest tomato trading centres in South India, plays a significant role in determining regional price trends. Weather-related production losses or supply disruptions in major producing belts often influence tomato prices across several neighbouring states, demonstrating the interconnected nature of vegetable markets.

Climate Variability and Tomato Markets

Climate variability is increasingly influencing agricultural production systems worldwide, and tomato cultivation is no exception. Changes in rainfall patterns, rising temperatures, and increased frequency of extreme weather events have introduced additional uncertainty into tomato production. Excess rainfall can increase disease incidence and reduce fruit quality, while prolonged dry spells may affect plant growth and productivity. Heat waves can accelerate fruit deterioration and reduce marketable yields. As climate change intensifies, production risks are expected to increase further. Consequently, climate-resilient cultivation practices and improved risk management strategies are becoming increasingly important for sustaining tomato production and stabilizing market prices.

Impact on Farmers and Consumers

Price volatility affects both producers and consumers, although in different ways. For farmers, low prices reduce profitability and increase financial stress. In extreme situations, farmers may leave produce unharvested because harvesting and transportation costs exceed expected returns. For consumers, sudden price increases raise household food expenditure. Tomatoes are a key ingredient in many Indian dishes, making them highly visible in discussions related to food inflation. Significant increases in tomato prices often affect the overall cost of preparing household meals. The coexistence of low farm-gate prices and high retail prices reflects inefficiencies within agricultural marketing systems and highlights the need for better coordination across the supply chain.

Building a More Stable Tomato Market

Reducing tomato price volatility requires coordinated efforts involving farmers, researchers, policymakers, market intermediaries, and private-sector stakeholders. The table illustrated below forms a clear idea of major problems and solutions.

Table 1 Major causes of tomato price volatility and possible solutions. Source: Adapted from National Horticulture Board (2024), Rhamya (2024), Kumar et al. (2025), and Pasupuleti et al. (2025).

Major Cause	**Impact on Prices**	**Impact on Farmers and Consumers**	**Possible Solutions**
Seasonal glut during harvest	Sharp decline in market prices	Farmers receive low returns and may resort to distress sales	Staggered planting, crop planning, and market intelligence services.
High perishability of tomatoes	Forced immediate sale after harvest	Farmers have limited bargaining power and suffer post-harvest losses	Improved storage facilities and cold chain infrastructure.
Inadequate cold storage facilities	Concentrated market arrivals	Excess supply during short periods causes price crashes	Expansion of cold storage and refrigerated transportation.

Limited processing capacity	Surplus produce remains unutilized	Wastage increases and farmer income declines	Promotion of tomato processing industries (ketchup, puree, paste, sauces)
Excessive rainfall and floods	Reduced production and supply shortages	Consumers face higher prices; farmers may suffer crop damage	Climate-resilient farming practices and improved drainage systems.
Drought and heat waves	Lower yields and poor fruit quality	Reduced market arrivals lead to price spikes	Efficient irrigation systems and heat-tolerant varieties.
Pest and disease outbreaks	Decline in marketable production	Production losses and higher market prices	Integrated pest and disease management practices
Supply chain and transportation disruptions	Delayed movement of produce	Local shortages and retail price increases	Better logistics, road connectivity, and supply chain management.
Lack of market information	Poor production and marketing decisions	Farmers may overproduce during favourable years	Digital market intelligence and price forecasting systems.
Weak farmer bargaining power	Lower farm-gate prices	Farmers receive a small share of consumer prices	Strengthening Farmer Producer Organizations (FPOs) and collective marketing.

Conclusion

Tomato price volatility remains one of the most visible examples of the challenges facing agricultural marketing in India. The tomato price paradox demonstrates that increased production alone does not guarantee higher farm income. Seasonal gluts, perishability, inadequate storage, weak processing infrastructure, climate variability, and supply chain inefficiencies all contribute to unstable prices. Addressing these challenges requires a combination of improved infrastructure, stronger farmer organizations, enhanced market intelligence, and climate-resilient production systems. By adopting a more integrated approach to production and marketing, India can create a more efficient tomato value chain that benefits both farmers and consumers while ensuring stable supplies and affordable prices.

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Farming with Intelligence: How Artificial Intelligence is Reshaping Agriculture for a Sustainable Future

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Abstract

Agriculture across the world stands at a historic crossroads. The twin pressures of a burgeoning global population and an increasingly erratic climate demand that farming evolve not just incrementally, but fundamentally. Artificial Intelligence (AI) has emerged as a transformative force capable of meeting these demands head-on. From intelligent crop advisory systems and soil health diagnostics to autonomous drones and predictive market platforms, AI is quietly but steadily rewriting the rules of modern farming. This article explores, in accessible language, how AI technologies are being applied in agriculture, what they mean for farmers particularly in India and how this intelligent revolution can be steered toward inclusive, sustainable growth.

Keywords: Artificial Intelligence, Precision Agriculture, Smart Farming, Sustainable Agriculture, Digital Farming, Food Security, India

1. Introduction: The Fields Need a New Brain

Imagine a farmer in Andhra Pradesh who wakes up at dawn and consults not just her instinct and experience, but a smartphone app that tells her exactly when to water her paddy, which corner of her field has nitrogen deficiency, and whether to expect a pest outbreak in the next two weeks. Just a decade ago, this would have sounded fantastical. Today, it is increasingly real. Agriculture has always been a knowledge-intensive enterprise it blends ecology, economics, biology, and weather reading in ways that challenge even the most experienced farmer. For centuries, this knowledge lived in the minds and hands of farming communities. But as climate patterns grow erratic, inputs become expensive, and markets turn volatile, traditional knowledge alone is no longer sufficient. What agriculture needs now is an amplification of that knowledge and that is precisely what Artificial Intelligence (AI) offers. AI refers to the capability of computer systems to learn from data, recognise patterns, make decisions, and solve problems in ways that mimic and often surpass human analytical ability.

In agriculture, AI does not replace the farmer. Rather, it equips every farmer with access to expert-level insights that were once available only to the well-resourced or the well-connected.

2. What Is AI-Powered Farming?

AI-powered farming integrates multiple technologies into a cohesive intelligent ecosystem. At its core lies the ability to collect large volumes of data from weather stations, satellites, soil sensors, drone cameras, and market feeds and then process this data rapidly to generate actionable recommendations.

Three foundational building blocks power this ecosystem:

- ✦ Data Collection: Sensors embedded in soil or carried by drones gather real-time information on moisture, temperature, nutrient levels, canopy health, and pest activity.
- ✦ Machine Learning: Algorithms trained on historical and real-time data identify patterns for instance, linking certain leaf discolouration signatures with specific fungal diseases.
- ✦ Decision Support: The system translates its analysis into farmer-friendly recommendations delivered through a mobile app, an audio message, or an SMS in the local language.

This feedback loop between data, analysis, and guidance is what makes AI-driven farming qualitatively different from all previous agricultural technologies.

3. Applications Transforming the Farm

3.1 Crop Health Monitoring and Disease Detection

One of the earliest and most impactful applications of AI in agriculture is the detection of crop diseases through image recognition. Farmers photograph leaves or stems using a smartphone, and AI models trained on thousands of images of healthy and infected plants instantly identify the disease or pest and recommend treatment. Studies have shown that such models can diagnose common diseases like rice blast, late blight in potatoes, and citrus canker with accuracy rates exceeding 90 per cent. The significance for smallholder farmers cannot be overstated. Disease outbreaks that once spread unchecked because a specialist was unavailable or unaffordable can now be caught early, saving entire harvests.

3.2 Precision Irrigation and Water Management

Water scarcity is a defining challenge of our era. In India, agriculture accounts for over 70 per cent of total freshwater use, and much of it is squandered through over-irrigation or poorly timed watering. AI-driven irrigation systems use soil moisture sensors and weather forecast data to determine, with precision, exactly how much water a crop needs and when. Farmers using such systems have reported water savings of 20 to 40 per cent, along with yield improvements, because crops receive water stress-free at optimal moments.

3.3 AI-Based Soil Health Diagnostics

Healthy soil is the foundation of productive farming. AI platforms now enable rapid soil health assessment by analysing data from portable soil testing kits or satellite-derived indices. These tools go beyond basic NPK readings to assess microbial activity, organic carbon levels, and compaction providing farmers with a nuanced portrait of their soil and tailored fertilisation recommendations. This not only improves yields but reduces the overuse of chemical fertilisers, which degrade soil health over the long run.

3.4 Drone and Satellite-Based Crop Surveillance

Agricultural drones equipped with multispectral cameras can survey hundreds of acres in a fraction of the time it would take a farmer on foot. AI algorithms process the aerial imagery to generate detailed field health maps highlighting stress zones, waterlogged areas, and weed infestations. Satellite-based platforms, several of which are now free-to-access for farmers, offer weekly or even daily crop monitoring at the village level, enabling timely interventions that prevent large-scale crop loss.

3.5 Market Intelligence and Price Forecasting

The tragedy of post-harvest price collapse is familiar to Indian farmers crops brought to market in glut fetch prices far below the cost of cultivation. AI-based market analytics platforms now offer price forecasting by analysing mandi arrival data, seasonal trends, and demand patterns across agri-value chains. Armed with this intelligence, farmers can make better decisions about harvest timing, storage, and market selection transforming them from price-takers into better-informed market participants.

4. AI in Indian Agriculture: Promise and Progress

India presents a uniquely complex landscape for AI adoption. With over 140 million farm holdings the majority smaller than two hectares and enormous diversity in crops, soils, languages, and literacy levels, scaling AI solutions here is a formidable but vital challenge.

The Government of India has recognised this potential. Key initiatives now underway include:

- Kisan e-Mitra: An AI-powered chatbot enabling farmers to access personalised crop advisory in regional languages, available round the clock.
- National Pest Surveillance System (NPSS): Uses AI to analyse pest trap data and weather patterns to issue real-time pest advisories to farmers and extension workers.

- Digital Agriculture Mission and AgriStack: A comprehensive framework to create a unified digital infrastructure for agriculture including a farmer registry, crop registry, and digital credit flow system that will serve as the backbone for AI-powered services.
- CROPIC and YES-TECH under PMFBY: Leverages remote sensing and AI to assess crop yields and expedite insurance claim settlements.

India's AI-driven agricultural journey is gaining momentum at the policy level. At the AI4Agri 2026 Summit held in Mumbai, the Government announced a clear strategic intent to position AI as the central pillar of farm policy, research, and investment, specifically targeting scalable productivity improvements for the country's hundreds of millions of small and marginal farmers.

5. Addressing the Sceptic: Challenges That Must Be Overcome

No transformative technology arrives without friction. For AI in agriculture, three structural challenges remain formidable:

- Digital Divide: Without reliable internet connectivity, smartphones, and electricity, AI tools cannot reach the farmers who need them most. Rapid rural infrastructure expansion through BharatNet and 5G rollout is a prerequisite.
- Data Quality and Localisation: AI models are only as good as the data they are trained on. Models developed with data from one agro-climatic zone may underperform in another. There is urgent need for India-specific, multi-crop, multi-region training datasets in regional languages.
- Farmer Trust and Usability: A farmer who has farmed for thirty years will not abandon her judgment for a machine recommendation she does not understand or trust. AI tools must be co-designed with farmers, explained in familiar terms, and demonstrated to work reliably across seasons before they achieve adoption at scale.

These are not insurmountable barriers. They are design and investment challenges and they are being actively addressed by a growing ecosystem of agri-tech startups, research institutions, and government programs.

6. The Sustainability Dividend

Beyond productivity, AI's most profound contribution to agriculture may well be environmental. By enabling site-specific and needs-based application of water, fertilisers, and pesticides, AI dramatically reduces the overuse of these inputs a chronic problem in conventional farming that degrades soils, contaminates water bodies, and generates greenhouse gas emissions. AI also strengthens agriculture's resilience to climate change. By integrating seasonal weather forecasts, climate trend data, and agronomic models, AI platforms can guide farmers on climate-smart crop choices, shifting sowing dates, and adaptive management practices effectively converting climate risk into manageable, plannable variables. In this sense, AI does not merely make farming more productive. It makes farming more responsible aligning agricultural practice with the planetary boundaries within which food systems must operate if they are to endure.

7. Looking Ahead: The Intelligent Farm of Tomorrow

The convergence of AI with other frontier technologies Internet of Things (IoT) sensors, blockchain-based supply chain traceability, gene-edited climate-resilient crop varieties, and autonomous farm machinery points toward a near future where agriculture is comprehensively data-driven, resource-precise, and environmentally accountable. Farmers of the next generation will not be less skilled they will be differently skilled. They will curate data, interpret AI recommendations with field wisdom, and manage intelligent systems. The extension worker of tomorrow will be part agronomist, part data interpreter, part digital navigator. For researchers, educators, and policymakers, this moment calls for purposeful action: investing in open, locally relevant datasets; designing AI systems with the farmer at the centre; and ensuring that the digital dividends of intelligent farming are shared equitably reaching women farmers, tribal communities, and rain-fed agriculture regions that have historically been left behind by agricultural progress.

8. Conclusion

Artificial Intelligence is not a panacea for the multifaceted challenges that agriculture faces. But it is, without question, one of the most powerful tools available to us as we navigate an era of climate uncertainty, resource scarcity, and growing food demand. Used wisely, AI can compress decades of agronomic learning into accessible, real-time guidance for every farmer with a phone in their hand. The vision is not of a farm where machines replace the farmer, but of a farm where every farmer regardless of the size of their holding or the depth of their pocket has access to the best agricultural knowledge that humanity has assembled. That is the promise of AI in agriculture. And the seeds of that promise are already in the ground.

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Protein Extraction from Plant-Based Waste Using Green Extraction Technology

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Abstract

The worldwide food production industry produces vast amounts of plant waste material each year ranging from fruit peels to vegetable pomace, and from oilseed press cake to cereal bran. Embedded within all this wasted biomass is an under-utilized source of valuable proteins. Although there exist well-established procedures for their separation from plant materials, the current methods employ numerous amounts of harmful organic solvents, huge energy requirements, and severe conditions that damage both proteins and the environment. A paradigm shift to greener extraction techniques is required in order to exploit biomass as an excellent source of valuable proteins.

Keywords: Plant waste biomass, Protein recovery, Green extraction techniques, Agro-industrial by-products, Sustainable food processing

1. Introduction: The Hidden Value in Plant Waste

The annual amount of plant biomass wasted in the agri-food sector worldwide amounts to hundreds of millions of tones. Just a few examples of such industrial-scale by-products include apple pomace, which comes from juicing; soybean meal, produced during oil pressing; tomato seeds and peel, from producing sauces; brewers' spent grain; and sugar beet pulp. All of these biomass streams contribute not only to the problem of greenhouse gas emissions, landfilling, and water pollution but also constitute a huge economic loss.

Among others, proteins are some of the most precious bioactive molecules contained in the waste streams mentioned above. The increasing demand for plant proteins derives from the rising global population, flexitarianism, and veganism, as well as the need to seek alternative ways to produce proteins in order to protect the environment. The protein composition in agro-industrial waste can vary between 5%, as seen in fruit pomaces, and over 40%, as seen in oilseed press cakes.

Extracting proteins from such waste streams is quite a challenging task. The proteins are embedded in complicated cellular matrices, and at times may be associated with polysaccharides, phenolic components, and lipids. The extraction procedures conventionally practiced include alkaline solubility and precipitation using their isoelectric point, and/or solvent-based techniques which work but entail considerable limitations, such as the employment of toxic solvents, the formation of acidic/alkaline effluents, and the denaturation of proteins due to heating processes. This is where green extraction technology steps into the scene.

2. Green Extraction

The concept of "green extraction" was formally articulated in the context of natural product chemistry, drawing from the twelve principles of green chemistry. In the context of protein extraction, green extraction refers to processes that:

- Minimize or eliminate hazardous solvents, replacing them with water, ethanol, or other GRAS (Generally Recognized as Safe) solvents
- Reduce energy consumption through optimized process conditions
- Maximize extraction yield and protein quality simultaneously
- Generate minimal waste or convert by-products into useful products
- Preserve biological functionality of the extracted proteins

The green extraction paradigm is not a single technology but a philosophy encompassing several innovative approaches, each suited to different waste streams and target applications.

3. Green Extraction Technologies

3.1 Ultrasound-Assisted Extraction (UAE)

The use of ultrasound in extracting proteins is based on the application of high-frequency sound waves (20–100 kHz), which cause acoustic cavitation within the liquid medium. The explosion of microbubbles leads to the creation of very high local pressures and temperatures, resulting in the disintegration of the cell wall structure and subsequent release of intracellular proteins into the solvent.

Some of the key benefits of using UAE to extract proteins from biomass include shorter times of extraction (minutes rather than hours), ability to perform extractions at relatively low temperatures, thus reducing denaturation. Various studies have shown an increased protein yield of between 15 and 40 percent when compared to traditional stirring techniques. The functionality of proteins extracted with UAE was also shown not to be compromised since parameters such as solubility, emulsification, and foaming were improved. The main drawback of UAE is associated with the scalability of the technology, which is challenging due to the difficulties in upscaling laboratory ultrasonic probes. Nonetheless, ultrasonic reactors have been developed.

3.2 Enzyme-Assisted Extraction (EAE)

The enzyme-assisted extraction takes advantage of the highly specific and effective action of biological enzymes for hydrolysis of cell wall compounds consisting mainly of cellulose, hemicellulose, and pectin which entrap proteins in plant materials. Among common enzymes used in EAE techniques are cellulases, hemicelluloses, proteases, pectinases, and xylanases, each or in combinations of different types.

EAE works on selective degradation of non-proteinaceous cellular matrix to yield proteins without necessitating extreme pH change or solvent use, hence making EAE especially suitable for extraction of protein from high-fiber materials like brewer's spent grains, sugar beet pulp, and hemp press cakes. Moreover, proteins extracted using this technique are found to be more soluble and digestible.

A notable advantage of EAE is its compatibility with mild, aqueous conditions at near-neutral pH, which preserves native protein structure and bioactivity. The main limitations are the cost of commercial enzyme preparations and the need to inactivate enzymes post-extraction to prevent over-hydrolysis. Research into cheap, microbially produced enzyme cocktails tailored to specific waste streams is actively addressing the cost barrier.

3.3 Pulsed Electric Field (PEF) Technology

Pulsed electric field technology involves the exposure of the plant material to short pulses of high electric energy (from 1 to 50 kV/cm for a period from micro- to milliseconds). Electric field creates electroporation – temporary or even irreversible openings in cell membranes which enables leakage of intracellular proteins and other biological macromolecules into the extracting medium.

PEF is a non-thermal process, which makes it particularly interesting for heat-labile proteins. This technology has been successfully employed in the extraction of fruit juices from potatoes (the waste product from starch production), microalgae, and several vegetable waste products. Energy consumption is relatively low when compared to thermal processes and can also be used for creating continuous processing lines. The PEF pre-treatment is usually complemented by other "green" processes, for example PEF treatment followed by centrifugation or ultrafiltration.

3.4 Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is mainly associated with the extraction of lipids (defatting) and not of proteins. However, SFE makes a huge contribution towards greening the protein extraction process. By extracting lipids from oilseed cakes using supercritical CO_2 before conducting any protein extraction, the process ensures that protein fractions produced are not affected by the use of any harmful chemical substances such as hexane, which is the industry-standard solvent for removing lipids from oilseed cakes.

Defatting meals using hexane-free methods through SFE is one of the key steps towards greening the process. Proteins extracted from hexane-defatted meals exhibit reduced solubility and functionality because their structures may be altered by heat and exposure to the solvent. Proteins isolated using SFE always possess higher functionality levels than those extracted using hexane. The only limitation of SFE is the relatively high initial costs of the equipment used.

3.5 Aqueous Two-Phase Systems (ATPS)

Aqueous two-phase systems refer to the spontaneous generation of two immiscible aqueous phases where a particular combination of polymers (such as polyethylene glycol and dextran) or polymers with salts (such as PEG and potassium phosphate) is dissolved above the critical concentrations. The surface properties of the proteins enable their separation into two phases.

Aqueous two-phase systems offer an environmentally friendly approach to protein isolation and separation through a completely aqueous process that eliminates the use of any organic solvent and extreme pH values. ATPS has been used effectively in the isolation and partial purification of proteins from the water associated with potato processing, green leaf material, and legumes. The incorporation of bio-derived compounds like starch and ionic liquids instead of petroleum-based polymers makes the technique even more sustainable.

3.6 Fermentation-Assisted Extraction

The use of solid-state fermentation or submerged fermentation employing generally safe microorganisms such as lactobacillus species, Aspergillus oryzae, and Rhizopus oligosporus provides a biological means of protein release. Enzymes produced by the microorganisms in the course of fermentation hydrolyze cell wall polysaccharides, decrease anti-nutritional compounds such as phytate and tannin contents, and sometimes elevate the total protein level through microbial biomass growth.

Fermentation becomes especially beneficial for the conversion of lignocellulosic materials whose proteins are difficult to isolate because of the presence of fibers that do not allow easy extraction. Various fermented cereal brans, leguminous hulls, and oil seed cakes have been found to exhibit higher protein solubility after microbial fermentation. The method requires low energy investment, employs inexpensive microbial inocula, and may result in simultaneous production of prebiotics and organic acids.

4. Plant-Waste Materials and Protein Extraction

4.1 Press Cakes from Oilseed Meals

Press cakes obtained after extraction from sunflower seeds, rape seeds, hemp seeds, flax seeds, or sesame seeds contain up to 20-40% proteins. At present, press cakes serve primarily as animal feed products of low value. Green extraction makes it possible to turn this material into valuable food protein concentrate or isolate.

4.2 Legume Processing Residues

The production of soy milk, tofu, and other legume-based foods generates okara (soy pulp) as a byproduct. Okara contains 20–30% protein on a dry-weight basis and is produced in millions of tons annually in Asia. EAE and fermentation approaches have shown particular promise in valorizing okara proteins due to its high moisture content and fiber matrix.

4.3 Cereal Bran and Brewers' Spent Grain

Wheat bran, rice bran, and brewers spent grain the fibrous residue from beer brewing collectively represent enormous volumes of protein-rich co-products. Brewers' spent grain contains approximately 20–25% protein and is produced at a rate of roughly 30 million tons per year globally. Ultrasound and enzyme-assisted processes have demonstrated effective protein extraction from these matrices.

4.4 Fruit and Vegetable Processing Residues

Tomato pomace, apple pomace, grape marc, and potato pulp contain more modest protein levels (5–15%) but are generated in such large volumes that even modest protein recovery represents a significant resource. The challenge here is the high moisture content and rapid perishability of fresh residues, which necessitates rapid processing or drying prior to4.3 Wheat Bran, Rice Bran, and Brewers’ Spent Grains

Wheat bran, rice bran, and brewers’ spent grains, which are the byproducts of beer production, constitute massive quantities of protein-filled byproducts. The protein content of brewers’ spent grain is around 20–25%, and it is made available on an annual global basis in a quantity of about 30 million tons. Protein extraction from these sources using ultrasound and enzymes has been successful.

4.4 Plant and Vegetable Residues

Tomato pomace, apple pomace, grape marc, and potato pulp have lower amounts of protein (5-15%), although they are produced in very large quantities, hence their potential as protein sources. However, the main difficulty with this source is the high level of moisture in the fresh material and its high perishability, requiring extraction shortly after collection or drying. extraction.

5. Challenges and Future Directions

Nevertheless, despite significant advances in the field, a number of issues should be solved to enable green extraction to become commercially competitive and gain traction in large-scale production. One of the crucial problems is the scaling-up of existing extraction techniques from lab to pilot scale. For instance, scaling-up of ultrasound-assisted, PEF-assisted, and enzyme-assisted extractions all require extensive engineering effort. Continuous flow processes seem to be more promising than batch systems. Many green extraction techniques lack economic competitiveness against traditional extraction procedures due to higher prices for enzymes, equipment, and longer time of operation. It is critical to carry out detailed techno-economic and life-cycle assessment to select the best possible approach. Regulatory issues should be considered carefully. Innovative protein extraction procedures may result in production of proteins with modified structure and accompanied by new substances used during the procedure; thus, regulatory approval is required prior to using these novel products in foods.

Protein functionality and allergenicity should be examined thoroughly. Modification of proteins in green extraction processes can affect their functionality in various manners, and the role of accompanying substances, such as polyphenols, requires investigation. In terms of future development perspectives, the application of several green technologies in the cascade biorefineries approach is most likely to yield good results. Single waste streams from plants can undergo multiple processes to isolate proteins, polyphenols, dietary fiber, and lipids, all of which may have potential applications in food/feed/cosmetic/pharmaceutical industries. The involvement of digital technology and intensification techniques, along with circular economy principles, will be crucial for achieving this objective.

6. Conclusion

The use of green technologies to recover proteins from plant-based waste presents an opportunity that brings together issues of sustainable development, economic efficiency, and innovation in the food industry. Such approaches as ultrasound-assisted extraction, enzyme-assisted extraction, pulsed electric fields, supercritical fluid treatment, aqueous two-phase systems, and fermentation have unique advantages and should be used selectively according to specific conditions. What is more important is the scale of benefits that can be gained by implementing these technologies: the transformation of agricultural and food processing waste into quality protein ingredients would decrease the amount of wastage and environmental impact of the industry significantly, promote further progress in bioeconomy, and provide new income opportunities.

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Haemorrhagic Septicaemia: A Major Threat to Cattle and Buffalo

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Abstract

Haemorrhagic septicaemia (HS) is one of the most important bacterial diseases affecting cattle and buffaloes, particularly in tropical and subtropical regions of Asia and Africa. Disease is caused by *Pasteurella multocida*, and characterized by acute septicaemia, high fever, and respiratory distress, swelling of the throat and neck region, and high mortality. Buffaloes are generally more susceptible than cattle, and outbreaks are often associated with during high humidity, heavy rainfall, transportation stress, poor nutrition, and inadequate management practices. Transmission occurs primarily through direct contact with infected or carrier animals and contaminated feed or water sources. Early diagnosis and proper treatment are important and vaccination is the most effective way for disease prevention and control. Biosecurity at farm, proper nutrition, stress reduction, quarantine of newly introduced animals, and farmer awareness can help to reduce the occurrence of disease. Effective control of Haemorrhagic septicaemia requires coordinated efforts among farmers, veterinarians, researchers, and government agencies.

Keywords: Haemorrhagic Septicaemia, *Pasteurella multocida*, Cattle, Buffaloes, Vaccination

Introduction

Livestock plays a crucial role in the agricultural economy of many developing countries. In India and several developing countries, cattle and buffaloes are the backbone of rural livelihoods. They are source of milk, manure, draft power, and source of income to poor and marginal farmers. However, livestock production is constantly threatened by various infectious diseases that can reduce productivity and cause substantial economic losses. Among these diseases, Haemorrhagic septicaemia (HS) is considered as one of the most fatal bacterial infections of cattle and buffaloes. The disease is important due to sudden onset, rapid progression, and sudden death of affected animal. Disease cause huge economic loss to countries due to significant mortality every year.

Etiological Agent

Haemorrhagic septicaemia is caused by a bacterium known as *Pasteurella multocida*. Bacteria is Gram-negative coccobacillus belongs to the family Pasteurellaceae appears as a small rod organism. It exhibits a characteristic bipolar staining pattern, and give safety-pin appearance on staining (Wilkie et al., 2012). The organism multiplying rapidly within the host once favourable conditions arise. The organism can persist in the upper respiratory tract of apparently healthy animals and such animals act as carriers and serve as a source of infection for susceptible livestock. Among several serotypes, specific serotypes are responsible for classical HS. In Asia, the disease is predominantly caused by serotype B:2. In Africa, serotype E:2 is most commonly associated with outbreaks (Bitew et al., 2025). Haemorrhagic septicaemia is widely distributed in tropical and subtropical regions and is commonly reported in India, Pakistan, Bangladesh, Nepal, Sri Lanka, Myanmar, Thailand, Malaysia, Indonesia, the Philippines, and several African countries (Almoheer et al., 2022). High humidity, elevated temperatures, and seasonal rainfall favour the disease transmission and outbreaks.

Epidemiology

Although cattle and buffaloes are the primary hosts of haemorrhagic septicaemia, the disease has also been reported in several other domestic and wild animal species, including sheep, goats, camels, horses, donkeys, pigs, yaks, deer, and various wildlife species (Cuevas et al., 2020). Buffaloes generally exhibiting higher susceptibility and mortality rates than cattle (Chanda et al., 2024). The disease is characterized by a distinct seasonal pattern, with outbreaks occurring more frequently during the monsoon season, periods of heavy rainfall, high humidity, and sudden climatic changes. Unfavourable environmental conditions enhance the survival and transmission of the causative organism, thereby increasing the probability of outbreaks. Animals of all ages are susceptible to HS; however, young animals often exhibit greater susceptibility and may develop severe disease. Adult animals lacking prior exposure or protective immunity can witness high mortality rates during outbreaks.

Transmission

The transmission of HS involves a complex interaction between infected animals, carrier animals, environmental conditions, and susceptible hosts.

- **Carrier Animals:** These animals appear healthy but harbour bacteria in their respiratory tract, shed organisms intermittently.

- **Direct Contact:** Healthy animals become infected through close contact with infected or carrier animals.
- **Respiratory Secretions:** Nasal discharge and respiratory droplets contain large numbers of bacteria and transmit to susceptible animals infected with contaminated droplets.
- **Contaminated Feed and Water:** Feed and water contaminated by infected secretions can serve as sources of infection.
- **Environmental Survival:** Wet soil, bedding materials and contaminated water sources may contribute to disease spread.
- **Animal Movement:** Movement of infected animals from one location to another can introduce the disease into previously unaffected areas.

Clinical Forms

The disease may appear in different forms depending on; Animal species, Immunity level, and Environmental conditions

Three clinical forms are commonly recognized:

Per-acute: The per-acute form of haemorrhagic septicaemia is the most severe and very fatal to animals. Affected animals may die suddenly without exhibiting noticeable clinical signs.

Acute: The acute form is most frequently observed in the field. Affected animals exhibit High fever, depression, reduced feed intake, excessive salivation, nasal discharge, neck swelling, respiratory distress,

Subacute: The subacute form progresses more slowly, affected animals may survive longer and respond better to treatment.

Clinical Signs

Early recognition of haemorrhagic septicaemia is essential because treatment is most effective during the initial stages of infection. The disease typically begins with a sudden onset of high fever, with body temperature often rising above 40–41°C. Affected animals become dull, depressed, and lethargic, showing a marked reduction in appetite and water intake. Lactating animals often exhibit a sudden decline in milk production, and affected cattle or buffaloes become weak and reluctant to move.

One of the most important signs of haemorrhagic septicaemia is the development of a painful swelling in the throat, neck, and dewlap region (Fig 1). Respiratory discomfort and animals exhibiting rapid and laboured breathing, open-mouth respiration, and abnormal respiratory sounds due to airway obstruction and lung involvement. In advanced stages, affected animals may become unable to stand, severe respiratory distress develops, frothy discharge and the mucous membranes become congested or cyanotic.

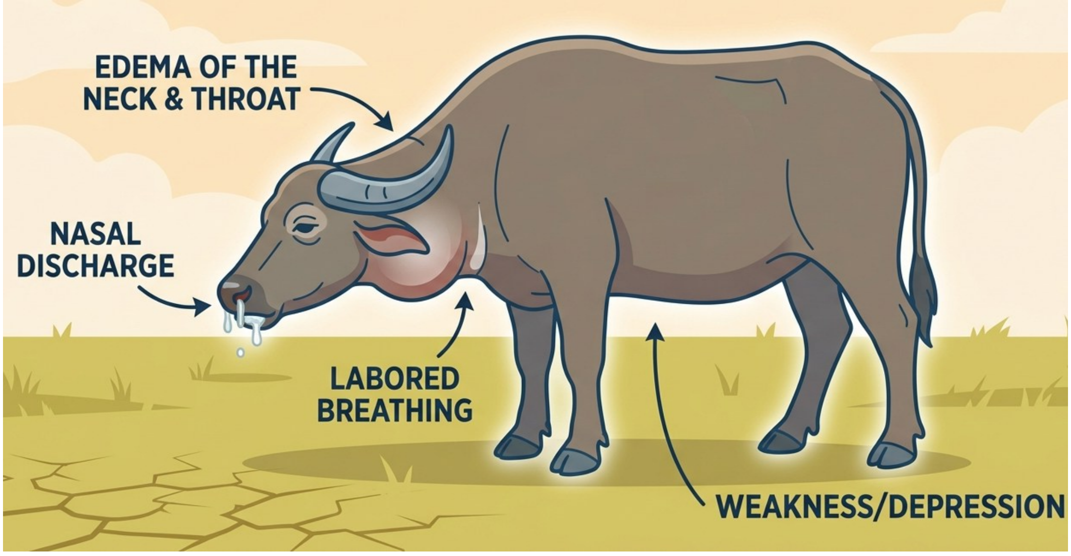

Fig. 1 Clinical symptoms of haemorrhagic septicaemia in buffalo (Image generated using Google Gemini AI)

Diagnosis

Accurate diagnosis is essential for effective disease control.

Clinical Diagnosis: Field diagnosis is based on history of sudden deaths, high fever, neck swelling, respiratory distress.

Laboratory Diagnosis: Definitive diagnosis of haemorrhagic septicaemia requires laboratory confirmation in addition to clinical observations and post-mortem findings. Common samples collected for laboratory examination include blood, nasal swabs, lymph node tissues, heart blood, and lung tissues from affected animals. Proper sample collection, handling, and transportation are essential to ensure accurate diagnostic results and successful isolation of the causative organism.

Economic Impact

Direct economic losses primarily arise from the death of valuable livestock. The loss of a high-producing dairy cow or buffalo leads not only the loss of a productive animal but significant financial investment. Milk yield may remain depressed for several weeks or months after recovery, further reducing farm income. Furthermore, farmers incur additional expenses related to veterinary consultations, diagnostic testing, medications, antibiotics, supportive treatment, and transportation of sick animal. The death of genetically superior breeding animals results in the permanent loss of valuable genetic resources. In addition, disease outbreaks may lead to restrictions on animal movement and trade, affecting livestock markets and income generation. Governments and animal health agencies also incur substantial costs for disease surveillance, outbreak investigations, vaccination campaigns, and implementation of control measures.

Treatment

Because haemorrhagic septicaemia progresses very rapidly, immediate treatment is essential for survival. The success of treatment largely depends on early recognition of clinical signs, rapid diagnosis, and prompt veterinary intervention. Animals treated during the initial stages of infection generally have a much better prognosis than those treated after the disease has become advanced.

In addition to specific antimicrobial therapy prescribed by a veterinarian, supportive treatment plays a crucial role in improving recovery and reducing complications. Fluid therapy is often administered to combat dehydration, maintain blood circulation, and prevent shock. Anti-inflammatory and antihistamines drugs help reduce fever, inflammation, and discomfort, thereby improving the animal's overall condition. Electrolyte supplementation helps restore fluid and mineral balance, which is often disturbed during severe illness. Furthermore, adequate nutritional support is important to provide essential energy and nutrients needed for recovery, enhance immune function, and improve the animal's ability to withstand the infection.

Vaccination

Vaccination is the most effective and economical method for preventing hemorrhagic septicemia and should be administered before periods of increased disease risk (Dhakarwal et al., 2025). Since most outbreaks occur during the monsoon season, animals should ideally be vaccinated several weeks before the onset of the rainy season. Similarly, animals scheduled for transportation, marketing, or movement to new locations should be vaccinated in advance, as transportation-related stress can increase susceptibility to infection. Vaccination plays a critical role in establishing herd immunity within livestock populations.

Biosecurity and Prevention

Effective biosecurity is an important measure for haemorrhagic septicaemia (HS) prevention and plays a crucial role in reducing disease outbreaks and associated economic losses.

- An important biosecurity measure is the quarantine of newly purchased animals before their introduction into an existing herd. Newly acquired animals should be kept in isolation for a suitable period to allow observation for any signs of illness, implementation of necessary vaccinations, and prevention of the introduction of infectious agents into the herd. Similarly, animals exhibiting clinical signs of HS should be immediately isolated from healthy animals.

- Regular cleaning of animal housing, proper drainage systems, routine disinfection of sheds and equipment, and the provision of clean drinking water help reduce environmental contamination and lower the risk of infection. Special attention should also be given to the proper disposal of carcasses.
- Balanced nutrition plays a vital role in enhancing the immune status of animals and improving their resistance to infectious diseases.
- Overcrowding, long-distance transportation, sudden dietary changes, and exposure to extreme weather conditions, can suppress immunity and predispose animals to infection. Therefore, minimizing these stress factors can significantly reduce the likelihood of disease occurrence.
- Strengthening veterinary infrastructure and ensuring timely access to veterinary care are essential for long-term disease prevention and control.
- Farmer awareness is perhaps one of the most effective tools for reducing disease losses.

Conclusion

Haemorrhagic septicaemia is a highly fatal bacterial disease of cattle and buffaloes that causes significant economic losses. However, it can be effectively controlled through timely vaccination, proper nutrition, biosecurity, and early veterinary intervention. Collaborative efforts among farmers, veterinarians, and policymakers are essential for sustainable disease prevention and livestock health.

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Poultry Vices: Hidden Habits That Reduce Farm Profitability

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Abstract

Poultry farming is one of the fastest-growing sectors of animal husbandry. However various behavioural disorders or vices can adversely affect bird welfare, productivity, and farm profitability. Poultry vices are abnormal behaviours that develop due to management, nutritional, environmental, or genetic factors and often result in significant economic losses. Common vices observed in poultry include cannibalism, egg eating, egg hiding, pica, and feather picking. Factors such as overcrowding, nutritional deficiencies, excessive light intensity, parasitic infestations, and stress contribute to the development of these undesirable behaviours. Early identification of risk factors and implementation of preventive measures are essential for effective control. Proper housing, balanced nutrition, adequate feeder and drinker space, appropriate lighting management, provision of nesting facilities, timely egg collection, debeaking and maintenance of flock health can significantly reduce the occurrence of vices. Understanding the causes and preventive measures of poultry vices is crucial for improving bird welfare, enhancing productivity, and ensuring sustainable poultry production.

Keywords: Poultry Vices, Cannibalism, Egg Eating, Feather Picking

Introduction

Poultry farming has rapidly evolved as one of the fastest-growing sectors, providing nutritious food security, generating employment opportunities for poor and marginal farmers of India (Singh et al., 2021; Ali J., 2007). Commercial poultry production systems are designed to increase the productivity by applying scientific balance feeding, proper housing, and management practices (Nassar, 2026). However, in spite of advancement in poultry management, behavioural changes, commonly known as "vices," prevail in poultry farm which continue to cause significant economic losses to poultry farmers.

Vices are undesirable and bad habits acquired by birds due to stress, nutritional deficiency, environmental stress, and improper management deficiencies. These habits spread rapidly within the flock and become difficult to control. It adversely affects bird growth, egg production, feed efficiency, and farm profitability. The most important poultry vices include cannibalism, egg eating, egg hiding, pica, and feather picking.

Cannibalism

Cannibalism is one of the most important vices of poultry flocks. In this condition, birds attack and peck other birds, causing severe injuries and sometimes death. The problem is particularly common in large commercial flocks where birds are kept under intensive management systems. Cannibalistic behaviour often begins with toe pecking in chicks, feather pecking in growing birds, and vent pecking in laying hens (Fig 1). Once birds become accustomed to pecking and tasting blood, the behaviour spreads quickly throughout the flock.

Several Factors Contribute to The Development of Cannibalism

Overcrowding: Insufficient floor and cage space increases stress among birds and lead to aggressive behaviour

Genetic Factors: Certain breeds of poultry like Leghorns are more prone to cannibalism.

Vent and Genital Injuries: During egg laying, the bright pink appearance of the vent attracts pecking from other birds and minor bleeding further stimulates pecking.

Protein and Amino Acid Deficiency: Inadequate dietary protein, particularly deficiencies of methionine and arginine, can trigger feather pecking and cannibalism.

Mineral and Salt Deficiency: Lack of minerals and salt promote abnormal feeding behavior.

Parasitic Infestation: External parasites like mites, ticks damage feathers and skin, creating wounds that attract pecking.

Sudden Dietary Changes: Sudden changes in feed composition can cause stress and abnormal feeding behavior.

Excessive Lighting: High light intensity and prolonged lighting periods in the farm increase bird activity and aggression.

Prevention and Control

- Provide adequate floor space according to the age and size of birds.
- Ensure balanced nutrition with sufficient protein, amino acids, vitamins, and minerals.
- Avoid sudden changes in feed formulation.
- Maintain proper ventilation and environmental conditions in the farm.
- Isolate injured birds immediately from other birds.

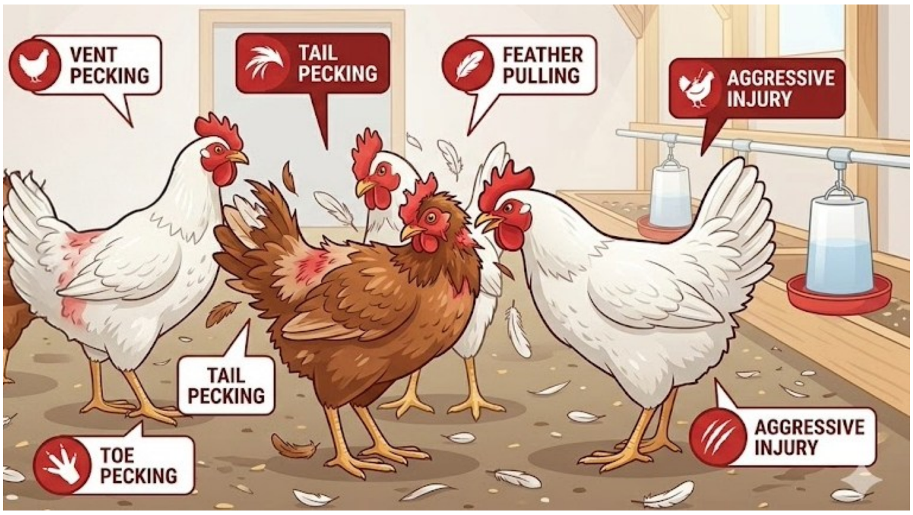

Fig. 1 Cannibalism in poultry (Image generated using Google Gemini AI)

- Provide adequate feeder and drinker space.
- Reduce excessive light intensity in poultry houses.
- Treat wounds promptly using suitable antiseptic preparations.
- Beak trimming (debeaking) has been used to reduce cannibalistic behavior. However, modern poultry welfare guidelines emphasize other management practices.

Egg Eating

Egg eating is another common vice in poultry, particularly among laying hens. Vice in bird start with accidentally broken eggs and gradually develop a habit of breaking and consuming eggs intentionally (Fig 2). Once established in the farm, the behavior can spread rapidly within the flock, leading to further damage to farm and economic losses.

Causes of Egg Eating

- Presence of cracked or broken eggs.
- Thin-shelled eggs resulting from calcium deficiency.
- Delayed egg collection.
- Inadequate nesting material.
- Overcrowding.
- Insufficient nest boxes.
- Excessively bright lighting.

Fig. 2 Egg eating vice in poultry (Image generated using Google Gemini AI)

Preventive Measures

- Collect eggs frequently throughout the day.
- Provide adequate nesting boxes.
- Use soft bedding materials such as straw or sawdust.
- Remove broken eggs immediately.
- Maintain appropriate calcium and vitamin D levels in feed.
- Train pullets to use nest boxes before the onset of laying.
- Reduce light intensity in nesting areas.
- Use roll-away nests where possible to move eggs away from birds immediately after laying.
- Early identification and removal of habitual egg eaters

Egg Hiding

Egg hiding is less common in commercial poultry production but is occasionally observed in backyard and free-range systems. Birds hide their eggs in bushes, grass, or secluded locations instead of laying them in nests and farm (Fig 3).

Fig. 3 Egg hiding vice in poultry (Image generated using Google Gemini AI)

Prevention

- Restrict unnecessary roaming of laying birds.
- Provide comfortable and attractive nest boxes.
- Use adequate nesting materials such as straw, wood shavings, or sawdust.
- Maintain a quiet and secure laying environment.
- Proper nest management significantly reduces the occurrence of hidden eggs and associated production losses.

Pica

Pica, also known as depraved appetite, refers to the consumption of non-nutritive materials such as feathers, litter, threads, paper, or other foreign objects. Although less common in modern poultry operations, pica can still occur when birds experience nutritional deficiencies or environmental stress.

Causes of Pica

- Phosphorus deficiency.
- Mineral imbalance.
- Parasitic infestation.
- Introduction of unfamiliar litter materials.
- Poor management practices.
- Birds suffering from pica may ingest large quantities of foreign materials, leading to digestive disturbances and crop impaction.

Prevention

- Provide balanced and scientifically formulated diets.
- Ensure adequate mineral supplementation.
- Control parasitic infestations.
- Maintain clean and suitable litter conditions.
- Follow good management practices.
- Proper nutrition remains the most effective preventive measure against pica.

Feather Picking and Feather Eating

Feather pecking is a behavioural disorder in which birds pull out and sometimes consume feathers from themselves or other flock members. The behaviour may begin through curiosity and imitation but can become a serious flock problem if not addressed.

Factors Associated with Feather Picking

- Nutritional deficiencies.
- Lack of grit in feed.
- Poor-quality feed.
- Digestive disturbances.
- Overcrowding and stress.
- Inadequate environmental enrichment.
- Feather loss exposes the skin, increasing the risk of injuries, infections, and cannibalism.

Prevention

- Maintain balanced nutrition.
- Provide adequate grit where necessary.
- Avoid overcrowding.
- Improve environmental enrichment.
- Identify and remove persistently affected birds when required.
- Early intervention is essential because feather-picking habits are often difficult to eliminate once established.

The Importance of Good Poultry Management

Most poultry vices arise from management-related factors rather than disease. Proper housing, balanced nutrition, adequate space, environmental control, and regular monitoring of bird behaviour are key to preventing these problems. Farmers should inspect their flocks daily and identify abnormal behaviours at an early stage. Timely corrective measures not only improve bird welfare but also enhance productivity and profitability.

Conclusion

Behavioural vices such as cannibalism, egg eating, egg hiding, pica, and feather picking pose significant challenges to poultry production. Although these habits may appear minor initially, they can rapidly spread through a flock and cause substantial economic losses. Most vices can be prevented through proper nutrition, scientific housing, good management practices, and regular observation of bird behaviour. By understanding the causes and implementing preventive measures, poultry farmers can maintain healthy flocks, improve productivity, and ensure sustainable poultry farming (Dolberg, 2007).

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Biofloc and RAS Only from The Standpoint of Ammonia Elimination

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Abstract

Ammonia accumulation is a critical issue in aquaculture systems due to its toxic effects on aquatic organisms, including reduced growth, increased oxygen demand, and elevated mortality. Approximately 78% of nitrogen in aquaculture systems originates from protein-rich feed, with only 25% contributing to animal growth and the remainder excreted as waste, ultimately forming inorganic ammonia. This article explores three primary ammonia transformation pathways: assimilation by photoautotrophic algae, oxidation by autotrophic nitrobacteria, and assimilation by heterotrophic bacteria. Among these, heterotrophic assimilation forms the basis of Biofloc Technology (BFT), an innovative approach that uses added carbon sources to stimulate microbial biomass growth, which efficiently uptakes ammonia while improving water quality. In contrast, Recirculating Aquaculture Systems (RAS) primarily rely on autotrophic nitrification for ammonia control, requiring precise management of oxygen, pH, and alkalinity. While RAS offers enhanced biosecurity and reduced water use, challenges remain in nitrate accumulation and system complexity. This review highlights the advantages and limitations of BFT and RAS, offering insight into sustainable ammonia management strategies for high-density aquaculture operations.

Keywords: Ammonia management, Biofloc Technology (BFT), Recirculating Aquaculture Systems (RAS), Nitrification, Aquaculture sustainability

Introduction

Ammonia accumulation remains one of the most critical challenges in aquaculture systems, particularly in the culture of high-protein feed-dependent species such as finfish and shrimp. As aquaculture practices intensify to meet global seafood demand, innovative strategies are essential to maintain water quality, ensure animal welfare, and support sustainable production. Among various nitrogen management approaches, Biofloc Technology (BFT) has emerged as a promising and environmentally sound method, especially for species like white-leg shrimp that require high dietary protein inputs. By harnessing the metabolic potential of heterotrophic bacteria to convert toxic inorganic nitrogen into microbial biomass, BFT offers both improved ammonia removal and enhanced nutrient recycling. This article explores the biochemical pathways of nitrogen transformation in aquaculture systems, with a particular focus on the mechanisms and advantages of BFT compared to traditional autotrophic nitrification and photoautotrophic uptake, and also examines its application alongside Recirculating Aquaculture Systems (RAS) to create integrated, low-waste production environments.

Ammonia Removal in Biofloc Technology Systems

Ammonia is a very poisonous inorganic nitrogen molecule used in aquaculture that damages fish and shrimp by lowering growth, increasing oxygen consumption, degrading water quality, and perhaps increasing mortality. About 78% of nitrogen in aquaculture water originates from feed, which is high in protein—25–30% for finfish and up to 40–45% for shrimp like white-leg shrimp. But feed use is inefficient: just 25% of nitrogen from protein helps animals grow, and about 75% of it ends up in the water as excrement, metabolic waste, or dissolved organic molecules, which microbes then break down into inorganic ammonia. The main routes for ammonia transformation in aquaculture. There are three routes for ammonia removal or transformation in aquaculture system: intake by photoautotrophic algae, nitrification and nitration of autotrophic nitrobacteria, and assimilation of heterotrophic bacteria.

Route 1: Photoautotrophic intake by algae or phytoplankton

Actually, the intake route of ammonia by photoautotrophic algae is the process of well-known photosynthesis as follows:

$$16\ NH_4^+ + 92\ CO_2 + 92\ H_2O + 14\ HCO_3^- + HPO_4^{2-} \rightarrow C_{10}6H_263O110N16P + 106\ O_2$$

Where, C106H263O110N16P represents the stoichiometric formula for algae.

In this procedure, the ionic ammonia of NH_4+ Is the first-order employed inorganic Nitrogen for synthesis of organic molecules. However, a carbon to nitrogen to phosphorus ratio (C:N:P) of roughly 106:16:1 is also required, meaning that exogenous additions of inorganic carbon and phosphorus sources are required to promote ammonia assimilation. This makes it generally difficult to control the growth of algae, particularly blue green algae or cyanobacteria, and can easily lead to cyanobacteria blooming, a major decline in water quality, and a catastrophe for human daily life.

Route 2: Autotrophic oxidation by nitrobacteria

Autotrophic nitrobacteria, the chemical autotrophic bacteria, can oxidize ammonia by using inorganic carbon sources without the need of phosphorus:

$NH_4^+ + 1.83\ O_2 + 1.97\ HCO_3^- \rightarrow 0.0244\ C_5H_7O_2N + 0.976\ NO_3^- + 2.9\ H_2O + 1.86\ CO_2$

Microbial biomass is represented by the chemical formula $C_5H_7O_2N$. The rate of nitrification is limited by the slower growth of nitrobacteria, which are in charge of ammonia oxidation, in comparison to heterotrophic bacteria. There are no efficient additives that hasten this organic process. Despite having enough dissolved oxygen, the production of a hazardous intermediate called nitrite (NO_2) oxidizes haemoglobin's Fe^{2+} to Fe^{3+}, obstructing oxygen transport and resulting in asphyxiation in aquatic animals. Additionally, nitrification causes nitrate (NO_3) to build up, which encourages algal blooms. It also reduces carbonate alkalinity (HCO_3^-), which lowers water pH and has an impact on water quality in general.

Route 3: Assimilation by heterotrophic bacteria

Ammonia also could be assimilated by heterotrophic bacteria through a process Different from those of photoautotrophic algae (route 1) and autotrophic Nitrobacteria (route 2)

$NH_4^+ + 1.18\ C_6H_{12}O_6 + HCO_3^- + 2.06\ O_2 \rightarrow C_5H_7O_2N + 6.06\ H_2O + 3.07\ CO_2$

Where the chemical formula for microbial biomass, such as route 2 or Eq. (5), is represented by $C_5H_7O_2N$. Although roughly half of the HCO3 will be used up, more dissolved oxygen is required for the bio-reaction of Eq. (6) processing than with route 2. In contrast, Eq. (6) of method 3 requires the production of carbohydrate ($C_6H_{12}O_6$) and produces roughly 40 times the amount of microbial biomass.

Biofloc Technology (BFT) is a novel approach to ammonia removal and reuse in aquaculture that is based on route 3. Although ammonia buildup is a significant problem in aquaculture, methods 1 and 2 are not appropriate for removing it. Using algae or phytoplankton in Route 1 may result in overgrowth, quick decomposition, and the release of toxins. The intricate procedures used in Route 2, which was created for sewage treatment, are inappropriate for aquaculture. However, biofloc technology (BFT), an efficient and environmentally responsible technique for ammonia transformation in aquaculture, was developed as a result of route 3.

Ammonia Removal in Recirculating Aquaculture Systems

By efficiently controlling ammonia levels and minimizing water exchange, Recirculating Aquaculture Systems (RAS) enable improved environmental management and increased fish stocking density. Autotrophic nitrification, a two-step process in which ammonia is transformed to nitrite by ammonia-oxidizing bacteria and subsequently to nitrate by nitrite-oxidizing bacteria, is responsible for maintaining ammonia levels below 1 mg L^{-1}. A low C/N ratio (0–1) is necessary for this process, which employs carbon dioxide as a carbon source and oxygen for bacterial growth. A C/N ratio of 2 can diminish nitrification efficiency by 70% (Zhu & Chen, 2001).

A sump, fish tanks, solids removal tanks, and bio-filtration (nitrification) tanks are commonly seen in RAS. The majority of the solids are trapped in solids removal machines, which receive water from fish tanks that are rich in both organic and inorganic waste. Water that has been clarified but still contains a lot of ammonia goes into the bio-filtration tanks to be nitrified. For additional treatments like UV, ozone, pH, and temperature control, purified water with minimal ammonia and solids travels to the sump. To facilitate nitrification, DO levels are kept between 5 and 6 mg L^{-1} (Colt, 2006). Bicarbonate is added to maintain a pH of about 7 after nitrification consumes alkalinity and causes pH reductions (Martins et al., 2009; 2010). To eliminate trapped particles and lower nitrate, the byproduct of nitrification, periodic water exchange is required (Ramli et al., 2017). In order to eliminate the requirement for water exchange, current research focuses on integrating denitrification units that employ solid wastes to lower nitrate levels (Fontenot et al., 2007; Ramli et al., 2008; Yogev et al., 2017). Turbidity < 1000 mg L^{-1} as an indirect indicator of the C/N ratio (Ramli et al., 2008), pH at 7, and DO $>$ 5 mg L^{-1} for fish and nitrification are the three main metrics to keep an eye on in RAS. Probes can measure DO and turbidity, but laboratory tests are necessary for C and N levels (Ebeling et al., 2006; Martins et al., 2010; Mota et al., 2015).

Conclusion

Ammonia management is a critical component of sustainable and intensive aquaculture practices. While traditional methods such as photoautotrophic assimilation and autotrophic nitrification provide avenues for ammonia removal, they present limitations including unstable algal growth and accumulation of harmful intermediates like nitrite and nitrate. In contrast, Biofloc Technology (BFT), which utilizes heterotrophic bacteria for ammonia assimilation, offers a more efficient and eco-friendlier alternative by converting waste nutrients into microbial biomass that can be reused within the system. Similarly, Recirculating Aquaculture

Systems (RAS) enable effective ammonia control through nitrification and advanced filtration processes, though they require precise management of water quality parameters such as dissolved oxygen, pH, and C/N ratio. Together, BFT and RAS represent modern, complementary strategies that can enhance water quality, reduce environmental impact, and support the intensification of aquaculture operations. Continued innovation and integration of these systems, including advances in denitrification and nutrient recycling, will be essential for meeting the growing demand for sustainable aquaculture production.

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The Hidden Challenge in Plant-Based Aquafeeds: Antinutritional Factors and Their Management

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Abstract

Plant-derived feed ingredients are being investigated as sustainable alternative protein sources in aquaculture to lessen reliance on fishmeal. However, these components frequently include antinutritional factors (ANFs) like phytates, tannins, saponins, protease inhibitors, and trypsin inhibitors, which can have a negative impact on fish health overall, growth performance, feed utilization, and nutrient digestibility. ANFs cause mineral shortages and compromised physiological activities in farmed animals by binding with vital nutrients and decreasing nutrient bioavailability. Thus, the development of plant-based aquafeeds that are economical, nutritious, and sustainable depends on the efficient control of ANFs. Numerous processing methods, such as fermentation, germination, soaking, and autoclaving, have been effectively used to lower the concentration of antinutritional chemicals and enhance the nutritional value of feed ingredients obtained from plants.

Keywords: Antinutritional factor (ANFs), Plant-derived nutritional substances, Aquaculture

Introduction

Plant protein sources have been used in the feed industry for a number of reasons, including sustainability, availability, and cost-effectiveness. Plants contain thousands of chemicals that, depending on the situation, might be beneficial or harmful to organisms that consume them. They are utilized fresh and raw, dried, powdered, boiled, fermented, concentrated, and so on. It is fed directly to herbivorous fish and as a supplement or partial replacement for fish meal in fish feed formulations. Plant sources are characterized as alternatives that can be employed in fish feed without affecting its nutritional quality. Plant-based fish feed has disadvantages due to poor protein content and certain anti-nutrients (Mondal and Payra, 2015). Legumes, ferns, and other non-traditional animal feed sources have anti-nutritional properties in both their green and dry stages.

Antinutritional Factors

Antinutritional factors are compounds that disrupt food use, growth, health, and reproduction in animals, either directly or through bio-transformation. Animals are susceptible to antinutritional influences, which have a negative impact on growth and health. Most antinutrients used in fish feed have poor physiological effects, stunted growth, and health difficulties, rather than causing mortality. Hypoglycemia, liver damage, pancreatic hypertrophy, and other pathological illnesses are linked to poor food conversion efficiency. The severity of these symptoms varies based on the amount of antinutrients consumed, animal species, size, age, and other physiological factors (FAO, 2018).

Antinutritional factors can be broadly classified into the following groups:

(a) Those affecting protein digestion such as protease inhibitors, lectins, tannins etc.
(b) Those affecting mineral utilization such as phytates, oxalates etc.
(c) The antivitamins (amthamines, antiriboflavins etc.) that have an impact on vitamin use.
(d) Other miscellaneous compounds, such as mycotoxins, phytoestrogens, saponins, etc.

Antinutritional factors can also be grouped according to their ability to withstand thermal processing, the most commonly known treatment for destroying them.

(a) Thermolabile (heat-sensitive): Reduced or inactivated by cooking, extrusion, roasting, or autoclaving. e.g., enzyme inhibitors, Lectins and certain alkaloids.
(b) Heat-resistant/thermostable: Dose not inactive by typical cooking or feed processing temperatures. e.g., Non-starch polysaccharides, phytic acid, saponins, and tannins.

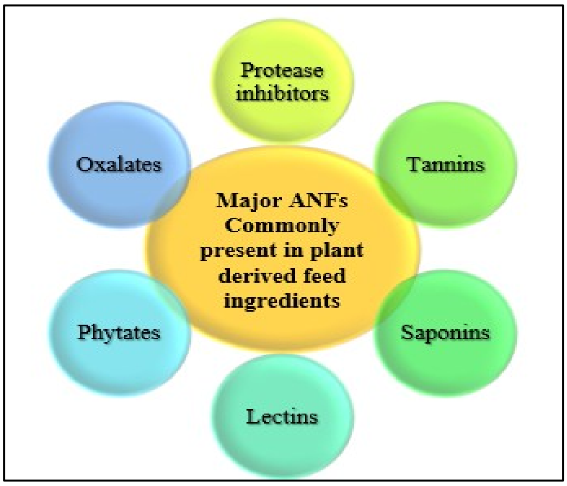
Major ANFs Commonly Present in Plant-Derived Feed Ingredients

Saponin

Saponins are widely distributed in nature, primarily in plants, and are generally regarded as non-volatile, surface-active secondary metabolites. Saponins are sugar-containing steroids or triterpenes. Many plant species, such as groundnuts, lupins, oil seeds, etc., naturally produce them as glycosides or triterpenes that produce foam.

Phytates

Phytates or phytic acids occur naturally in the plant kingdom. Phytic acid is a secondary compound that is typically present in all plant-based meals and naturally concentrates in plant seeds, particularly in legumes, peanuts, cereals, and oilseeds.



Tannins

Tannins are secondary chemicals found in plant leaves, fruits, and bark. Tannins generate reversible and irreversible tannin-protein complexes between their hydroxyl group and the carbonyl group of proteins, reducing protein digestibility and critical amino acid levels. Tannins interact with proteins, inactivating digestive enzymes and reducing protein digestibility.

Protease inhibitors

These chemicals can inhibit enzymes from performing proteolytic functions. They can be found in all plants, but are particularly common in legumes such as soybeans. These inhibitors attach to digestive enzymes such as chymotrypsin and trypsin, rendering them partially or completely inert.

Lectins or Hemagglutinins

These are proteins that have a high affinity for sugar molecules. The name refers to the agglutination of red blood corpuscles (RBCs). Hemagglutinins can be found in seeds of higher plants. They continue to be present in Plant saps and tubers. Lectins reduce nutrition absorption from the gut or alimentary canal. These chemicals can cause internal hemorrhages. They also reduce growth.

Oxalates

Oxalates in feed ingredients can prevent fish from absorbing certain nutrients. For example, certain critical minerals, such as calcium, which is required for bone formation, a number of metabolic activities, and the cofactor requirements of multiple enzymes, have low bioavailability.

Strategies Used to Reduce ANFs Levels in Plant-Derived Feed Ingredients

Various traditional and technical processes, including soaking, milling, roasting, boiling, germination, and fermentation, have been used to reduce anti-nutritional components in food. This article discusses processing methods for reducing phytate, tannin, and saponin concentrations in foods.

Milling

Milling is the most traditional process for separating the bran layer from the grains. This is the process of grinding grains into flour. Milling eliminates anti-nutrients from grain bran, including phytic acid, lectins, and tannins.

Soaking

In this procedure, plant materials are soaked in water to remove water-soluble ANFs (tannins, phytates) that diffuse into the medium. Soaking increased phytase activity, reduced grain phytate content, decreased phytochemicals, and drained water-soluble vitamins and minerals from grains and legumes. Soaking improves nutritional availability and digestion. It is a simple, low-cost pre-treatment procedure with variable effectiveness.

Heat treatments

heat treatment reduces ANFs in plant feed ingredients by Inactivating heat liable ANFs such as protease inhibitors and lectins by unfolding the protein structure. It includes boiling, autoclaving, pressure cooking, extrusion cooking, and toasting. Cooking or boiling at 100 °C for 60 minutes was enough to inactivate over 90% of the trypsin inhibitor activity in food. Autoclave for 30 minutes at 125 °C and 15 Ib pressure to remove thermolabile inhibitory compounds (saponins, terpenoids, alkaloids).

Germination

In this approach, whole grams are soaked overnight and then knotted in a loose cotton cloth after being removed from the water. Seed germination activates phytase, which degrades phytate and reduces phytic acid concentration in the sample. Germination alters the nutritional content, biochemical properties, and physical characteristics of foods. This approach is widely used to reduce the anti-nutritional content of cereals

Fermentation

Fermentation is a microbial process in which microorganisms (bacteria, fungus, or yeast) create enzymes that convert ANFs to non-toxic, edible forms. Furthermore, this improves nutrient availability, feed efficiency, and promotes fish growth and health.

Conclusion

Plant-based feed ingredients are essential for sustainable aquaculture, however antinutritional factors may significantly affect nutrient uptake, growth performance, and fish health. A detailed understanding of their mechanisms and species-specific impacts, together with appropriate mitigation techniques, enables the creation of nutritionally efficient, cost-effective, and environmentally sustainable aquaculture feed.

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Etiology, Pathology and Management of Major Fish Diseases: A Comprehensive Review for Sustainable Aquaculture

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Abstract

Fish diseases caused by viral, bacterial, fungal, and parasitic agents remain a primary constraint to global aquaculture productivity. This review synthesizes current knowledge on the etiological agents, pathological manifestations, epidemiological determinants, and evidence-based management strategies for major infectious fish diseases. The 'disease triangle' framework comprising host susceptibility, pathogen virulence, and environmental perturbation is employed to analyze disease dynamics. Environmental stressors, particularly temperature fluctuations, deteriorating water quality, and intensive stocking, are identified as critical predisposing factors that compromise host immunity and facilitate pathogen establishment. A systematic categorization of viral (VHS, IHN, SVC), bacterial (Columnaris, MAS, Edwardsiellosis, Furunculosis, BKD, EUS), fungal (Saprolegniasis, Branchiomycosis), and parasitic diseases (Myxosporidiosis, Dactylogyrosis, Argulosis) is presented along with their clinical profiles and recommended chemotherapeutic and prophylactic regimens. The review underscores the urgent need for integrated health management protocols and advances in immunoprophylaxis and environmentally sustainable biocontrol strategies.

Keywords: Aquaculture pathology, Ichthyopathology, Disease triangle, Chemotherapy, Immunoprophylaxis, Integrated fish health management

1. Introduction

Global aquaculture has experienced exponential growth over recent decades, now contributing over 50% of fish for human consumption (Little et al., 2016). Despite this remarkable expansion, infectious disease outbreaks remain the most significant biological and economic constraint to sustainable fish production. Mortality events attributable to pathogenic organisms result in annual losses estimated in the billions of US dollars, severely undermining food security objectives in both developed and developing economies. Disease pathogenesis in fish is fundamentally multifactorial, governed by the complex interactions captured within the classical 'disease triangle': the vertebrate host, the etiological agent, and the ambient environment (Scholthof, 2007). Under conditions of environmental stress - including rapid temperature shifts, dissolved oxygen depletion, hypercapnia, elevated unionised ammonia, and excessive stocking density host immune competence is compromised, creating conditions permissive to opportunistic infection and frank pathogen invasion (Cascarano et al., 2021). Mishra et al. (2017) documented that the majority of disease outbreaks in Indian freshwater aquaculture are directly precipitated by deterioration of water quality parameters, a finding corroborated by extensive field observations across tropical and subtropical production systems.

This article systematically examines the principal infectious diseases affecting cultured fish, with emphasis on their etiological basis, pathological manifestations, and contemporary management approaches. Understanding these disease processes at a mechanistic level is essential for the development of rational, evidence-based intervention strategies that minimize reliance on broad-spectrum chemotherapy (Noga, 2010; Shrivastava et al., 2025).

2. Predisposing Environmental and Management Factors

The onset of infectious disease in fish populations rarely follows simple host-pathogen dyad dynamics. Environmental perturbations function as the primary gateway through which pathogens gain advantage over host defense mechanisms. Svobodova et al. (1993) identified thermal fluctuation as the single most important environmental trigger, with thermal stress inducing cortisol-mediated immunosuppression and rendering fish susceptible to a broad spectrum of pathogens.

Water quality parameters of critical significance include dissolved oxygen (optimal range 5–8 mg/L), pH (6.5–8.5), un-ionized ammonia (<0.02 mg/L), and carbon dioxide (<10 mg/L). Turbidity elevation associated with organic loading reduces the phagocytic efficiency of immune effector cells and promotes proliferation of facultative pathogens. Anthropogenic inputs - agricultural runoff, industrial effluents, and municipal wastewater introduce xenobiotic compounds that synergistically suppress host immunity while simultaneously elevating pathogen burdens in the water column. High stocking densities exacerbate these stressors by increasing waste metabolite accumulation, physical injury through conspecific aggression, and facilitating horizontal pathogen transmission (Cascarano et al., 2021; Carlino-Costa & Belo, 2025).

3. Major Infectious Disease Groups: Etiology and Clinical Profiles

3.1 Viral Diseases

Viral infections in fish are particularly challenging due to the absence of effective chemotherapeutic agents and the limited availability of licensed vaccines for most pathogens. Table 1 summarizes the major viral diseases, their etiological agents, and characteristic clinical presentations.

Table 1 Major viral diseases of fish: Etiology and clinical signs

Disease	Causative Agent	Key Symptoms	Reference
Viral Haemorrhagic Septicaemia (VHS)	*VHSV (Novirhabdovirus)*	Exophthalmia, haemorrhagic skin discolouration, abdominal distension, lethargy; high mortality in salmonids	Meyers & Winton, 1995
Infectious Haematopoietic Necrosis (IHN)	*IHNV (Rhabdoviridae)*	Abdominal distension, exophthalmia, skin darkening, fecal casts, anaemia; acute mortalities in salmonid fry	LaPatra, 1994
Spring Viraemia of Carp (SVC)	*SVCV (Rhabdoviridae: Vesiculovirus)*	Haemorrhagic ascites, pale gills, exophthalmia, petechiae; principally affects cyprinids in spring	Waltzek et al., 2005

Viral haemorrhagic septicaemia virus (VHSV) represents one of the most economically significant fish pathogens globally, affecting over 80 species across Eurasia and North America. The virus causes severe systemic haemorrhagic disease in rainbow trout and numerous marine species, with mortality rates approaching 100% in susceptible populations under acute infection. In the absence of licensed therapeutics, management relies exclusively on stringent biosecurity protocols, regular population surveillance, and chlorine-based disinfection of water systems (Meyers & Winton, 1995). IHN similarly lacks approved pharmacological interventions, with disease control dependent upon isolation of infected stocks, elimination of carrier fish, and implementation of epidemiological testing protocols (LaPatra, 1994). SVC, caused by a Vesiculovirus, remains notifiable to the World Organisation for Animal Health (WOAH) due to its rapid spread among cyprinid populations and associated production losses (Waltzek et al., 2005).

3.2 Bacterial Diseases

Bacterial pathogens constitute the most diverse and economically impactful group of infectious agents in aquaculture. Their capacity to exploit stressed hosts renders them particularly problematic in intensive production systems. Table 2 presents the principal bacterial diseases encountered in cultured fish.

Table 2 Principal bacterial diseases of fish: etiology, clinical signs

Disease	Causative Agent	Key Symptoms	Reference
Columnaris Disease	*Flavobacterium columnare (syn. Flexibacter columnaris)*	Greyish-white epidermal lesions; saddle-shaped dorsal ulcers; gill necrosis; 'cottonwool' appearance	Davis, 1922; Declercq et al., 2013
Motile Aeromonad Septicaemia (MAS)	*Aeromonas hydrophila, Pseudomonas fluorescens*	Haemorrhagic ascites, hepatic necrosis, exophthalmia; systemic septicaemia	JSTAGE, 2019; Austin & Austin, 2007
Edwardsiellosis	*Edwardsiella tarda*	Scale loss, skin lesions, malodorous muscle gas cavitations; necrosis of musculature	Vincent, 2012; Mohanty & Sahoo, 2007
Furunculosis	*Aeromonas salmonicida*	Haemorrhagic septicaemia; muscle boil-like lesions (furuncles); blood-stained exudate	Cain & Polinski, 2014; Bernoth & Körting, 1992
Bacterial Kidney Disease (BKD)	*Renibacterium salmoninarum*	Swollen kidney; granulomas; abdominal fluid; white viscous intestinal content	Wiens & Kaattari, 1999
Epizootic Ulcerative Syndrome (EUS)	*Aphanomyces invadans + Aeromonas spp.*	Chronic deep red ulcers; 'cauliflower' mouth deformity; skin necrosis	Kar, 2015

Columnaris disease, caused by *Flavobacterium columnare* (previously classified as *Flexibacter columnaris*), affects a wide spectrum of commercially important freshwater species and is associated with significant mortality particularly in warm-water conditions (Davis, 1922). Motile *Aeromonad* Septicaemia (MAS), primarily attributed to *Aeromonas hydrophila*, is an opportunistic infection of global prevalence, invariably associated with environmental stressors and compromised host immunity (JSTAGE, 2019). Bacterial Kidney Disease, caused by the Gram-positive *Renibacterium salmoninarum*, is among the most challenging bacterial infections in salmonid aquaculture due to its intracellular lifestyle, vertical transmission, and resistance to conventional antibiotic regimens (Wiens & Kaattari, 1999). Epizootic Ulcerative Syndrome, classified as a notifiable disease by WOAH, has caused catastrophic losses in Asian freshwater fisheries, with *Aphanomyces invadans* now established as the primary mycotic agent in a polymicrobial pathogenesis model (Kar, 2015).

3.3 Fungal and Parasitic Diseases

Fungal infections in fish are predominantly secondary conditions precipitated by prior physical trauma, nutritional deficiency, or immunosuppression. Saprolegnia spp. remain the most prevalent aquatic fungi affecting freshwater teleosts globally, causing characteristic cotton-like mycelial growths that penetrate host tissues and precipitate inflammatory responses (Robertson et al., 2009). Branchiomycosis, caused by *Branchiomyces sanguinis* and *B. demigrans*, produces necrotic gill pathology and respiratory compromise, often culminating in acute mortality (Özcan & Arserim, 2022).

Among protozoan parasites, *Ichthyobodo necator* (previously *Costia necatrix*) is a ubiquitous obligate ectoparasite responsible for costia disease, characterized by grayish-white epidermal films and haemorrhagic patches (Becker, 1977). *Myxobolus cerebralis*, the causative agent of whirling disease, invades cartilaginous tissues of salmonid juveniles, producing severe skeletal deformity and characteristic whirling locomotor disturbance (Bruno et al., 2006). Monogenean trematodes of the genera Dactylogyrus and Gyrodactylus are among the most prevalent and economically significant ectoparasites in freshwater aquaculture, causing extensive gill and skin pathology through mechanical abrasion and mucus hypersecretion (Mhaisen & Abdul-Ameer, 2019; Cojocaru, 2007). Crustacean ectoparasites, including *Argulus* spp. (fish lice) and *Lernaea* spp. (anchor worms), cause significant physical trauma, immune suppression, and predispose infested fish to secondary bacterial infections (Misganaw & Getu, 2016).

4. Integrated Disease Management Strategies

Effective fish disease management necessitates a multi-pronged integrated approach encompassing preventive, therapeutic, and prophylactic dimensions. Prophylactic pond management remains the foundational strategy: pre-stocking disinfection with quicklime (400–600 kg/ha in new ponds; 500–800 kg/ha in old ponds) and bleaching powder (50–100 kg/ha) effectively reduces environmental pathogen loads. Routine disinfection of equipment with 5–25 ppm formalin or 250 ppm KMnO4 prevents cross-contamination between production units (Noga, 2010).

Therapeutic intervention protocols include primary chemical treatments using potassium permanganate (2–3 ppm pond application; 100–250 ppm bath treatment for 2–3 min), copper sulphate (1–2 ppm), and sodium chloride (2–3% bath treatment). Antibiotic therapy, where pathogen susceptibility is confirmed, employs oxytetracycline (50–60 mg/100 kg fish/day for 15 days per os), erythromycin phosphate (1 mg/kg BW for BKD), and sulphonamide compounds. Parenteral antibiotic administration (streptomycin 25 mg + penicillin 20,000 IU/kg BW) is reserved for high-value broodstock exceeding 1 kg. Critical management principles include maintenance of optimal stocking densities, provision of nutritionally balanced diets, regular netting (bi-monthly), and monthly water exchange of 30 cm depth (Noga, 2010; Shrivastava et al., 2025).

5. Conclusion

Fish infectious diseases, arising from the complex interplay of pathogen virulence, host susceptibility, and environmental determinants, constitute one of the most pressing challenges confronting global aquaculture. An integrative, evidence-based approach to disease management combining rigorous environmental monitoring, prophylactic chemotherapy, nutritional optimization, and emerging immunoprophylactic technologies is essential for the long-term sustainability of intensive fish production. Future research priorities must encompass the development of efficacious vaccines, host-specific probiotics, and biological control agents that reduce dependence on broad-spectrum antibiotics, thereby mitigating the risk of antimicrobial resistance and ensuring the production of safe aquatic food products.

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Altaf et al. (2026)

Biomagnification and Its Ecological Consequences in Aquatic Ecosystems

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Abstract

The process by which the concentration of harmful contaminants rises at successive trophic levels in an aquatic food chain is known as biomagnification. Through agricultural runoff, industrial discharge, urban wastewater, atmospheric deposition and persistent pollutants such heavy metals, pesticides, herbicides, microplastics, oil hydrocarbons and industrial effluents infiltrate aquatic environments. These contaminants build up in aquatic species and grow more concentrated in higher trophic levels, especially in predatory fish, aquatic birds and mammals, since they are resistant to degradation. Numerous ecological effects of biomagnification include neurotoxicity, immunological suppression, developmental anomalies, reproductive impairment and increased mortality. Additionally, it reduces biodiversity, modifies community structure, disturbs food-web dynamics and lowers ecological productivity. Additionally, microplastics facilitate the spread of contaminants across food chains by acting as transporters of hazardous substances. Consuming seafood puts human health at serious risk due to the buildup of contaminants in commercially relevant fish species. To reduce biomagnification and preserve the sustainability of aquatic ecosystems, efficient pollution control and environmental monitoring are crucial.

Keywords: Biomagnification, Aquatic pollution, Food web, Heavy metals, Microplastics, Human health risk

1. Introduction

Emerging pollutants are mostly novel compounds that have been discharged into water bodies in significant amounts due to social and economic changes over the past few decades, posing a risk to aquatic ecosystems. (Zenker et al., 2014). Particularly when it comes to the management of dredged materials, the possible ecological implications of pollutants connected with sediment are concerning (Suedel et al., 1994). Understanding and measuring the fate, bioaccumulation, exposure and potential for negative impacts of chemicals discharged into the environment is of interest to both scientists and regulators. In comparison to concentrations at lower trophic levels, trophic biomagnification across a food chain or food web can significantly raise chemical concentrations at higher trophic levels, hence increasing exposure and possible risk (Mackay et al., 2016).

Some authors define biomagnification as the increase in concentration between trophic levels; if the biomagnification factor (concentration in predator/concentration in prey) >1, the compound is biomagnified. The standard definition of biomagnification is the transfer of a xenobiotic chemical from food to an organism, resulting in a generally higher concentration within the organism than source (Gray, 2002). Rapid development over the past few decades has increased atmospheric emissions, especially from non-ferrous metal smelters and geothermal plants (Zhang et al., 2020).

Water (waterborne uptake) and food particles (foodborne uptake) are the many sources of uptake for aquatic species. However, bioaccumulation and bioavailability are considered together in ecotoxicological research. Studying bioaccumulation without taking bioavailability into account would be impossible and vice versa. Therefore, both are taken into consideration here together with the application of bioaccumulation in biomonitoring. In particular, the pathways of exposure and internalization in the cell and organism determine the rate of uptake of designed nanomaterials and their negative effects (Gupta et al. 2017). Based on the exposure route, there are three primary types of uptakes, as seen in Fig. 1: bioconcentration, bioaccumulation and biomagnification. Biomagnification poses the greatest threat to human health and the environment out of the three (Uddin et al., 2020).

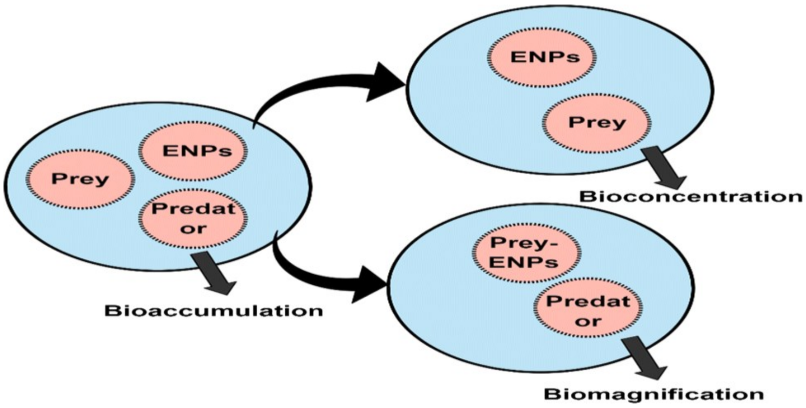

Fig. 1 Conceptual illustration of bioaccumulation, bioconcentration, and trophic biomagnification of engineered nanoparticles (ENPs) in aquatic ecosystems (Uddin et al., 2020)

2. Historical Background

This article traces the history of persistent, bioaccumulative and toxic chemicals (PBTs) from Faraday's 1825 synthesis of technical benzene hexachloride (BHC) to the ongoing global initiatives to phase out 12 persistent, organic pollutants (POPs) under the United Nations Environmental Program (UNEP). The search for new applications for chlorine in the 1930s resulted in the development of several chlorinated insecticidal compounds, such as DDT, which won Müller the Nobel Prize in Medicine for its remarkable effectiveness in controlling typhus, malaria, typhoid fever and cholera both during and after the War.

DDT and other PBTs/POPs raised environmental concerns in the 1960s because they bioaccumulate and biomagnify in food chains, harming wildlife reproduction. Their high lipid solubility causes them to accumulate in organisms, leading to global efforts to control their use and disposal.

Multimedia emissions and volatility also cause long-distance environmental movement through water and the atmosphere, which contaminates humans and biota at locations far from their use. The United Nations Environmental Program (XJNEP) Governing Council organized an international working group in May 1995 to create evaluations for 12 POPs. Aldrin, chlordane, dieldrin, DDT, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, PCBs, polychlorinated dibenzofurans (PCDFs) and polychlorinated dibenzo-p-dioxins (PCDDs) are the twelve POPs (Lipnick & Muir, 2000).

3. Sources of Toxic Pollutants in Aquatic Ecosystems

3.1 Agricultural Sources

Pesticide

Pesticides and agrochemicals in general have grown in importance in the world's agricultural systems, allowing for notable gains in crop yields and food supply. Fish species and other aquatic organisms that are a part of the tropical food web have been shown to be severely poisoned by pesticides. Invasive and harmful pests are controlled with pesticides in forestry, agriculture and landscaping. They can travel great distances and could potentially enter the hydrological cycle at any time (Ray & Shaju, 2023).

Herbicides

Runoff and drainage from agricultural fields are the primary ways that herbicides can find their way into surface waters. Wastewater treatment facilities, storm sewers, or a combination of sewer overflows and runoff from metropolitan areas are urban sources of herbicide pollution to surface water (Vonk & Kraak, 2020).

3.2 Industrial Sources

Heavy Metals (Mercury, Cadmium, Lead and Arsenic)

Surface water systems may contain heavy metals from both natural and man-made sources. Volcanic eruptions, weathering of rocks containing metals, sea salt sprays, forest fires and natural weathering processes are examples of geological and ecological sources that can start the release of metals from their native skies to various environmental areas. Heavy metals can be found in various forms, including hydroxides, oxides, sulphides, sulphates, phosphates, silicates and organic molecules (Sonone et al., 2020).

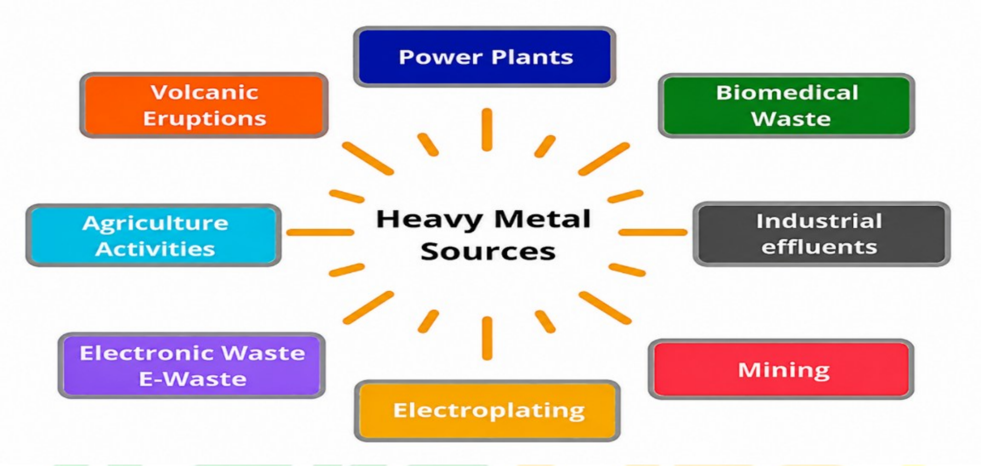

Fig 2. Different sources of contamination heavy metal in water

Industrial effluents

Some of the main sources of pollution include household sewage, municipal garbage and industrial waste that is directly released into the natural water system. Water contamination results from untreated waste discharge. The discharge of untreated manufacturing effluents into water bodies is the main cause of contamination of surface and groundwater (Sonone et al., 2020).

3.3 Urban Sources

Pharmaceutical Residues

Wastewater from a range of industrial, agricultural and residential sources is constantly released, which can contaminate freshwater habitats with pharmaceuticals. Animal and human excrement are the main sources of this pollution. Only a portion of the active substances in medications are metabolized; the remainder are eliminated in the urine or faces. These drug residues enter the wastewater system mostly through toilets and drains. Wastewater and other aqueous systems are contaminated by veterinary medications (Aib et al., 2025).

Microplastics

Plastic pollution in aquatic ecosystems is largely caused by wastewater discharge. Untreated and inadequately treated wastewater can directly dump microplastics into aquatic environments. Basin waters are one of the primary sources of MPs in water bodies, as are the microplastics transported by household effluent from washing machines, outlets and showers. Microfibers from synthetic fabrics like polyester are released in large quantities from laundry wastewater in particular. Up to 1900 fibres can be released in a single wash. Additionally, this pollutant burden is increased by personal care items that contain synthetic microplastics and microbeads. If these MPs are not processed, they end up in sewage and eventually accumulate in water bodies (Aib et al., 2025).

4. Mechanism of Biomagnification

The concept of biomagnification, in which a chemical is moved up the food chain to higher trophic levels and its concentration in predators exceeds what is anticipated when an organism and its surroundings are in equilibrium, is shown in Fig. 3. The measurement of an organism's bioconcentration, trophic transfer, and biomagnification in an ecosystem can be better understood by using several terminologies that lead to different processes (Saidon et al., 2024).

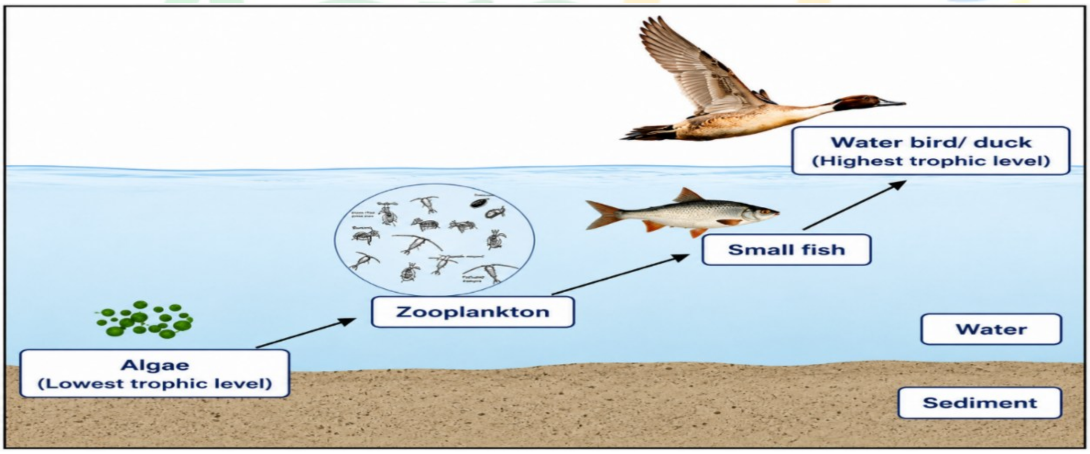

Fig. 3 The trophic transfer from organism at lowest trophic level to highest trophic in an aquatic ecosystem (Saidon et al., 2024)

5. Ecological consequences in aquatic ecosystems

5.1 Heavy Metals

Among the most hazardous contaminants in aquatic environments are heavy metals like mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As). They remain in water and sediments for decades since they are not biodegradable. Following phytoplankton absorption, these metals ascend the food chain and accumulate more in fish, birds, and aquatic mammals. Neurotoxicity, reproductive dysfunction, developmental problems, immunological suppression, decreased growth, behavioural disorders, and mortality are all consequences of this biomagnification. The highest quantities are accumulated by top predators, who frequently experience significant physiological stress and population decreases.

Table 1 Ecological consequences of heavy metal biomagnification

Ecological Consequence	Description	Example
Neurotoxicity	Damage to nervous system	Mercury poisoning in tuna
Reproductive impairment	Reduced fertility and hatchability	Cadmium in fish
Growth reduction	Stunted growth and poor development	Lead exposure in fish
Immune suppression	Increased disease susceptibility	Arsenic contamination
Biodiversity loss	Decline of sensitive species	Mining-affected rivers

5.2 Pesticides

After entering water bodies through agricultural runoff, persistent pesticides including DDT, Endosulfan, Aldrin, and Dieldrin build up in aquatic food chains. These substances affect hormone production, interfere with endocrine systems, and hinder reproductive processes. Predatory fish and fish-eating birds are particularly vulnerable to the biomagnification of pesticides. Eggshell thinning, decreased hatchability, aberrant development, and population decreases are all consequences of prolonged exposure.

Table 2 Ecological consequences of pesticide biomagnification

Ecological Consequence	Description	Example
Eggshell thinning	Weak eggs break during incubation	DDT in pelicans
Endocrine disruption	Hormonal imbalance	Endosulfan exposure
Embryonic defects	Abnormal development	DDT-contaminated fish
Reduced fertility	Fewer offspring produced	Fish populations
Population decline	Long-term reduction in abundance	Aquatic birds

5.3 Herbicides

The main way that herbicides like Atrazine, Glyphosate, Paraquat, and Simazine impact aquatic ecosystems is by decreasing the productivity of aquatic plants and phytoplankton. Higher trophic levels are indirectly impacted by herbicide contamination because these creatures are the base of aquatic food webs. Lower oxygen generation, less food availability, and changed community organization are the outcomes of reduced photosynthesis.

5.4 Microplastics

Plankton, molluscs, crabs, and fish consume microplastics, which physically harm their digestive systems. Toxic substances including heavy metals and persistent organic pollutants are also transported by them. Microplastics cause physiological stress, inflammation, decreased feeding efficiency, poor reproduction, and the spread of harmful compounds across food webs through biomagnification.

Table 3 ecological consequences of herbicide contamination

Ecological Consequence	Description	Example
Reduced photosynthesis	Inhibition of plant growth	Atrazine
Lower oxygen levels	Reduced dissolved oxygen	Glyphosate
Food-web disruption	Less food for consumers	Aquatic ecosystems
Habitat degradation	Loss of aquatic vegetation	Paraquat
Reduced productivity	Lower biomass production	Simazine

Table 4 Ecological consequences of microplastic biomagnification

Ecological Consequence	Description	Example
Digestive blockage	Reduced nutrient uptake	Fish and shellfish
Reduced feeding	Lower food consumption	Zooplankton
Tissue inflammation	Internal injuries	Marine fish
Reproductive impairment	Lower fertility	Mussels
Toxic chemical transfer	Adsorbed pollutants transferred	Marine food webs

5.5 Oil hydrocarbons

Oil spills and industrial discharges produce oil hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAHs). When these substances build up in aquatic species, they can result in cellular damage, genetic changes, aberrant growth, decreased reproductive success, and even death. Additionally, eating, migratory, and predator-prey relationships are all hampered by oil pollution.

Table 5 Ecological consequences of oil hydrocarbon biomagnification

Ecological Consequence	Description	Example
Genetic damage	DNA alterations	PAH exposure
Developmental defects	Abnormal growth	Fish larvae
Reduced reproduction	Lower spawning success	Marine fish
Behavioural changes	Altered feeding and movement	Crustaceans
Mortality	Death of aquatic organisms	Oil spill events

5.6 Industrial effluents

Heavy metals, dyes, medications, hydrocarbons, detergents, and hazardous organic compounds are all mixed together in industrial effluents. Chronic pollution and biomagnification result from ongoing discharge into aquatic habitats. These contaminants disrupt physiological systems, decrease biodiversity, change species composition, and upset ecological processes.

Table 6 Ecological consequences of industrial effluent biomagnification

Ecological Consequence	Description	Example
Biodiversity loss	Decline of sensitive species	Polluted rivers
Community alteration	Dominance of tolerant species	Industrial lakes
Physiological stress	Organ damage	Fish populations
Food-web disruption	Altered trophic interactions	River ecosystems
Ecosystem degradation	Reduced ecosystem health	Industrial zones

6. Human Health Implications

Bioaccumulated and biomagnified chemicals can cause serious health problems in humans. According to studies, neurological and developmental issues can be brought on by heavy metals like lead and mercury that are biomagnified through aquatic food webs. highlights how methylmercury buildup in fish has a major impact on human brain function, especially in young children and pregnant women.

There are also serious dangers associated with persistent organic pollutants like dioxins and polychlorinated biphenyls (PCBs). Numerous negative effects, such as immune system suppression and an elevated risk of cancer, have been connected to PCB exposure. Factors including age, sex and underlying medical issues frequently make the effects of these substances worse (Awafung et al., 2025).

7. Conclusion

In aquatic food webs, biomagnification is a crucial environmental mechanism that raises the concentration of persistent harmful contaminants at successive trophic levels. Aquatic ecosystems are contaminated by heavy metals, pesticides, herbicides, microplastics, oil hydrocarbons, industrial effluents, agricultural runoff, industrial discharge, urban wastewater, and other human activities. These pollutants build up in aquatic species and become more concentrated at higher trophic levels because of their persistence and resistance to degradation. Therefore, biomagnification has a variety of negative ecological effects, such as neurotoxicity, impaired reproduction, aberrant development, immunological suppression, loss of biodiversity, disturbance of the food chain, and deterioration of ecosystems. Because they acquire the largest quantities of contaminants, top predators such as humans, marine mammals, and fish-eating birds are especially at risk. Aquatic biodiversity, environmental stability, and human health are all seriously threatened by these contaminants' rising prevalence. Therefore, to lower pollutant inputs and lessen the negative effects of biomagnification, effective pollution control methods, sustainable waste management practices, ongoing environmental monitoring, and stringent regulatory laws are crucial. Long-term environmental sustainability, biodiversity conservation, and ecological balance all depend on the preservation of aquatic ecosystems.

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Madhulika (2026)

Antimicrobial Resistance in Aquaculture: The Silent Threat Beneath the Water

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Abstract

Aquaculture has emerged as one of the fastest-growing food production sectors and is essential for global food and nutritional security. However, the increasing use of antibiotics to control bacterial diseases has contributed to the emergence and spread of antimicrobial resistance (AMR), a major threat to aquatic animal health, environmental sustainability, and public health. Aquatic environments serve as important reservoirs of antibiotic residues, resistant bacteria, and resistance genes, facilitating their dissemination through water systems, seafood, and interactions between farmed and wild organisms. The rise of AMR compromises disease management, reduces treatment efficacy, and leads to significant economic losses in aquaculture. Moreover, the interconnected nature of humans, animals, and the environment highlights the need for a One Health approach to address this growing challenge. Sustainable alternatives, including vaccination, probiotics, improved biosecurity, and precision technologies, offer promising solutions to reduce antibiotic dependence. Combating AMR requires coordinated global efforts to ensure the long-term sustainability and resilience of aquaculture systems.

Keywords: Aquaculture, Antimicrobial resistance, Food security, Health

Introduction

Aquaculture is one of the fastest-growing food-producing sectors of the world and supplies more than half of the aquatic food consumed worldwide. Aquaculture is becoming a critical pillar of global food security in the face of a growing world population and increasing demand for high-quality protein. Fish, prawns and other aquatic organisms are a crucial source of nutrition and livelihood for millions of people worldwide. However, alongside this remarkable growth, the sector is facing an increasing challenge that threatens not only aquaculture production, but human and environmental health as well antimicrobial resistance (AMR). Antimicrobial resistance (AMR), often referred to as the "silent pandemic," occurs when microorganisms, particularly bacteria, evolve the ability to survive exposure to antimicrobial agents that were once effective against them (Watts et al., 2017). Antimicrobial resistance (AMR) is a natural evolutionary process driven by selection pressure; however, the extensive use of antimicrobials and various aspects of modern human activities have significantly accelerated the emergence and spread of latent or precursor resistance genes in bacterial populations (Deng et al., 2025).

The spread of resistant microbes makes infections harder to treat, leading to higher mortality, increased healthcare costs and reduced effectiveness of life-saving medicines. AMR is often thought of as a human medicine problem, but aquatic environments have become significant reservoirs and transmission routes of antimicrobial resistance. The emergence of antimicrobial resistance in aquaculture is a multifaceted issue with ramifications for fish health management, environmental sustainability, food safety, and public health (Madhulika et al., 2025b). Understanding the ways in which resistance develops and spreads is essential to ensuring the long-term sustainability of aquaculture worldwide.

Why Are Antibiotics Used in Aquaculture?

Aquatic animals are also affected by infectious diseases due to their biological nature, as is true for any organism. Intensive production systems create conditions that put animals under stress, and as animals are stressed by living in high density, this creates favourable conditions for the spread of disease from one animal to another through the transmission of pathogens (bacteria) (Deng et al., 2025). When a disease outbreak occurs from a bacterial infection in aquaculture, there can be a significant economic loss, which leads to the use of antibiotics to help farmers treat or prevent diseases. In aquaculture, antibiotics are commonly administered through medicated feeds or by direct application to the culture water for the prevention and treatment of bacterial diseases (Pepi and Focardi, 2021). These methods are successful in preventing or controlling the spread of bacterial infection; however, there can be negative effects caused by overuse or misuse of antibiotics and/or failing to diagnose the cause of a disease. The use of antibiotics in aquatic systems has its own unique challenges compared to their use in land-based livestock systems. Antibiotics may enter subsystems of aquaculture (ponds, tanks, rivers, lakes, and coastal waters), and as they enter the aquatic environment, they may not only affect the bacteria that they are intended to treat, but also other microorganisms. The widespread application of antibiotics in aquaculture creates an environment conducive to the selection, persistence, and dissemination of antibiotic-resistant bacteria (Watts et al., 2017).

How Does Antimicrobial Resistance Develop?

Bacteria have incredible flexibility in nature. The vast majority of the bacteria that have the potential to be impacted by antimicrobial treatment are destroyed; however, a select few will have some genetic ability to maintain their existence and continue to reproduce (Natrah et al., 2025). The use of antimicrobial agents promotes the spread of antimicrobial-resistant bacteria. The mechanisms by which microorganisms may develop resistance include natural mutations as well as gaining genes of resistance from others via conjugation, transformation, and transduction. In effect, within the microbial population, there is the capability of knowledge to be exchanged among bacteria, allowing for a rapid dissemination of resistant organisms throughout multiple environments and between species. The continuous exposure of antimicrobials upon bacteria fosters selective pressures to favour resistant organisms and hastens the development of antimicrobial resistance (Deng et al., 2025).

Aquatic Environments: A Reservoir for Resistance

Aquatic environments support extensive microbial growth and facilitate the widespread dispersal of microorganisms through water. When antibiotics are added to aquatic environments, residual antibiotics can remain in the sediment, water column and the surrounding environment. The presence of residual antimicrobials creates an environment for the persistence and growth of resistant microbes (Natrah et al., 2025). Fish farms typically support a large population of diverse microbes, including beneficial bacteria, opportunistic pathogens, and environmental microorganisms. The presence of antibiotics creates an opportunity for resistance genes to be exchanged between these groups of microbes, resulting in vast reservoirs of antimicrobial-resistant bacteria (Reverter et al., 2020). The issue of antimicrobial resistance is not limited to aquaculture facilities; the water that is discharged from aquaculture facilities can introduce resistant bacteria and resistance genes into rivers, lakes, estuaries and coastal ecosystems; therefore, the spread of antimicrobial resistance can occur well beyond the original point of antibiotic usage. This interconnectedness of the world indicates that the problem of antimicrobial resistance is a global environmental problem, not just a problem at the aquaculture farm level (fig. 1) (Watts et al., 2017).

The One Health Perspective

Modern strategies to prevent antimicrobial resistance are becoming more collaborative, integrating the idea of One Health into their strategy, which looks at how human beings, animals, and the environment all interact with one another in ways that affect each other's health. Aquaculture provides opportunities for that interaction. Antimicrobial-resistant bacteria account for an estimated 35,000 annual deaths in the USA, 33,000 in the European Economic Area, and 58,000 in India, with potentially greater mortality in Southeast Asia; these numbers are expected to continue rising (Reverter et al., 2020).

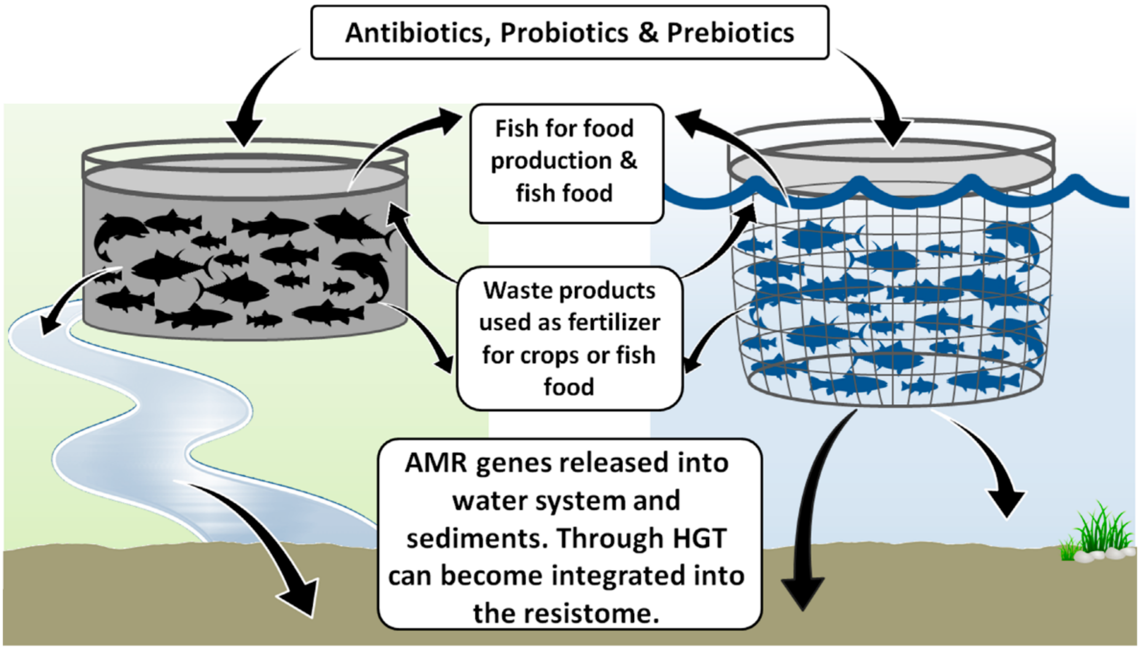

Fig. 1 Pathways of antimicrobial resistance (AMR) in aquaculture. Figure taken from Watt et al. (2017), under CC BY 4.0.

Fish farms are located in close proximity to natural bodies of water, allowing microorganisms to transmit between fish that are raised in aquaculture and those in the wild, as well as to and from freshwater and saltwater bodies, the environment, and humans. For example, bacteria that have become resistant to antimicrobials will typically enter the human food chain through seafood. Furthermore, resistance genes can be spread through water systems, thereby potentially affecting humans, livestock, and wildlife. Additionally, resistant bacteria from hospitals and agricultural runoff can also infiltrate aquatic systems and, therefore, impact the microorganisms that are present in aquaculture establishments (Watts et al., 2017). As a result, the transfer of microorganisms will continue to occur on a global scale; therefore, no one sector can prevent the emergence of antimicrobial resistance on its own. The only way to stop antimicrobial resistance is through coordinated action among human health, veterinary medicine, agriculture, aquaculture, and environmental management.

Consequences for Aquaculture

Antimicrobial resistance is becoming an increasing threat to aquaculture. As bacteria develop resistance to traditional antibiotics, it becomes more challenging for farmers to manage outbreaks of these diseases. Because of this, farmers may experience larger numbers of fish lost due to disease, poor growth rates and economic losses associated with reduced productivity (Madhulika et al., 2025b). In addition, the lack of efficacy of currently used antimicrobial treatments limits management options. In difficult situations, resistant bacteria can spread rapidly through a farm's production cycle, which jeopardises the entire production cycle. Higher therapy costs and reduced productivity may make aquaculture farms less financially viable. In addition, the concern about antimicrobial resistance can create a negative impact on consumers' trust and trade internationally. Many countries have established strict limits on residues of antibiotics and the use of antimicrobials in seafood. Failure to comply with these regulations can limit access to markets and result in financial losses to producers (Natrah et al., 2025).

Environmental Impacts

There are still many ways that the effects of antimicrobial resistance on the water environment can be impactful. One of these includes impacts due to antibiotics being introduced into aquaculture facilities. When antibiotics are placed into the water, they will change the microbial communities and ecological processes of that aquatic ecosystem (Reverter et al., 2020). Over time, microorganisms that provide nutrient cycling, decomposition of organic material, and ecosystem functioning can be impacted by long-term exposure to antibiotics. Sediments will collect and hold both the antibiotic residues and resistance-gene building blocks over time. The sediment provides a good environment for genetic exchange between all of the microorganisms which contributes to the persistence and spread of resistance. In addition to these things, the spread of antibacterial resistance into the aquatic environment is of great concern in regard to the conservation of biodiversity (Pepi and Focardi, 2021). Wild fish and other aquatic organisms could be exposed to pathogens that are resistant to available antibiotics, which will likely have negative effects on the health of the ecosystem and its ability to recover after disruption

Climate Change and Antimicrobial Resistance

Research is growing into how climate change could complicate the problem of antimicrobial resistance even more. Higher water temperatures will allow many different types of bacterial pathogens to grow and spread more rapidly. In addition, higher temperatures may alter the make-up of microorganisms (microbial community composition) and increase the chances of transferring resistance genes (Pepi and Focardi, 2021). Natural disasters, such as floods and storms, can also spread more resistant bacteria and antibiotic contamination among the different parts of a waterway. As climate change creates additional stresses for aquatic organisms, they may be more likely to contract diseases that will result in the greater use of antibiotics (Madhulika et al., 2025a). The relationship between climate change and antimicrobial resistance contributes to the need for integrated and forward-thinking management strategies.

Alternatives to Antibiotics

While we've made progress in the development of alternatives to decrease the reliance on antimicrobial treatments for aquaculture, it is more recent vaccinations that are now considered the most successful disease prevention method in aquatic animal production. Vaccination is effective because vaccines stimulate the development of protective immunity in the host, which decreases the incidence of diseases and rightfully reduces the need for antimicrobial treatment (Madhulika et al., 2025a). Probiotics are live microorganisms that improve gut health and improve the resistance of animals to disease. Probiotics help the host animal to resist infection from pathogens, enhance the immune response of the animal, and create a healthy balance of the resident microbiota of the animal. Prebiotics are non-digestible substances that specifically encourage the growth of beneficial gut microorganisms. Synbiotics are a combination of prebiotics and probiotics, so therefore maximize the health effects of both types of additives. Synthetic pre-and-probiotic feed additives are becoming increasingly popular as sustainable alternatives to antimicrobials (Natrah et al., 2025). Phytogenic Compounds (plant-derived bioactive compounds) possess antimicrobial, antioxidative, and immune-stimulating properties and therefore, a great deal of research is currently being conducted on the use of herbal extracts and essential oils as natural alternatives for disease management. Improving management practices is the key to preventing diseases in aquaculture. Proper stocking density, improved water quality, biosecurity measures, and proper nutrition are all important ways to reduce the incidence of diseases and the reliance on antibiotics to treat those diseases (Madhulika et al., 2025b).

Challenges and Recommendations

Antimicrobial resistance is an example of a global health issue that calls for collaboration; this includes input from all stakeholders, farmers, scientists, regulators, industry partners and consumers) (Natrah et al., 2025). Promoting responsible antibiotic use can be achieved by educating and creating awareness of proper use among all stakeholders involved. Strengthening regulations through surveillance systems to monitor antimicrobial use and the patterns of resistance can improve data collection efforts. Investing in research to develop new ways to prevent AMR and understand the novel mechanisms for developing AMR is critical to succeeding with AMR issues (Deng et al., 2025). Finally, aquaculture must shift from a treatment-based management strategy to a preventative management strategy by concentrating on fish health, environmental sustainability and ecosystem resilience.

Conclusion

Antibiotic overuse and misuse significantly threaten modern aquaculture technologies, but they have historically provided effective ways to control bacterial diseases. Due to misuse and overuse, antibiotic-resistant microorganisms have developed that threaten animal health, environmental sustainability, and public health. Also, the challenge of AMR goes far beyond aquatic animal farming as these interconnected ecosystems are impacted through many complex pathways. The expansion of the global aquaculture industry further emphasizes the need for effective sustainable disease management strategies. Sustainable aquaculture management of AMR in addition to developing globally sustainable food production systems will be developed by adopting responsible antibiotic use, building strong biosecurity protocols, vaccinating fish, nutritionally balancing fish diets through functional feeds, utilizing advanced technologies, and developing a One Health approach. The issue of antimicrobial resistance will not be resolved through one solution but by developing a coordinated approach to protect all components of our planet's ecosystems: aquatic livestock, ocean ecosystems, and humans, now and in the future. Responsible AMR management is an imperative for the future of sustainable aquaculture.

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Prajapati et al. (2026)

Forest Landscape Restoration for Climate Change Adaptation

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Abstract

Climate change has become a major global challenge causing rising temperatures, irregular rainfall, extreme weather events, biodiversity loss and land degradation. These impacts threaten ecosystem stability, agricultural productivity and human livelihoods. In this context Forest Landscape Restoration (FLR) has emerged as an effective strategy for climate change adaptation and ecosystem recovery. FLR is a long-term process that aims to restore ecological functionality and improve human well-being across deforested or degraded landscapes. It focuses not only on increasing tree cover but also on restoring ecosystem services, biodiversity, soil health and water resources. By enhancing resilience against droughts, floods and other climate-related stresses, FLR supports sustainable development and strengthens adaptive capacity. This article highlights the concept, principles, benefits, challenges and future prospects of FLR in the context of climate change adaptation.

Keywords: Climate change, Forest landscape restoration, Land degradation, Ecosystem services, Sustainable development, Adaptive capacity

1. Introduction

Climate change is significantly altering natural ecosystems through rising temperatures, changing precipitation patterns, prolonged droughts, floods and increased frequency of extreme weather events. These changes accelerate forest degradation, reduce biodiversity and weaken ecosystem resilience. Deforestation and unsustainable land-use practices further worsen environmental degradation by increasing greenhouse gas emissions and reducing the capacity of ecosystems to adapt to climate stress.

In response to these challenges, Forest Landscape Restoration (FLR) has gained global recognition as a holistic approach to restoring degraded landscapes. FLR goes beyond conventional tree planting by integrating ecological restoration with social and economic objectives. The primary aim of FLR is to regain ecological integrity while improving human well-being across entire landscapes. By restoring forests and associated ecosystems FLR helps communities adapt to climate variability and strengthens long-term environmental sustainability.

2. Concept of Forest Landscape Restoration

Forest Landscape Restoration is a planned process that seeks to regain ecological functionality and improve human well-being in deforested or degraded forest landscapes. Unlike traditional afforestation programs that mainly focus on tree plantation, FLR emphasizes restoring the overall landscape, including forests, grasslands, wetlands, agricultural lands and community resources. (Mansourian, 2005; Maginnis & Jackson, 2007)

FLR is based on principles such as:

- Restoring ecological integrity
- Enhancing biodiversity conservation
- Improving livelihood opportunities
- Increasing resilience to climate change
- Promoting stakeholder participation

3. Importance of FLR for Climate Change Adaptation

Forest Landscape Restoration (FLR) plays a vital role in helping both ecosystems and human communities adapt to climate change by enhancing ecological resilience and restoring degraded landscapes (Chazdon, 2008). Restored forest landscapes improve environmental stability by increasing vegetation cover, strengthening soil structure and enhancing water retention capacity, all of which are essential for coping with climate-related stresses. Healthy forest ecosystems are better able to withstand and recover from disturbances such as prolonged droughts, floods, landslides, heat waves and erratic rainfall patterns thereby reducing vulnerability to extreme climatic events. FLR supports climate adaptation through multiple interconnected pathways including improved water regulation which helps maintain hydrological balance and ensures water availability during dry periods reduced vulnerability to drought through enhanced groundwater recharge and better moisture conservation and improved soil moisture retention which supports vegetation growth and agricultural productivity even under water stress (IUCN & WRI, 2014). Additionally, FLR contributes to the stabilization of degraded lands by reducing soil erosion, controlling desertification and restoring land productivity. These ecological improvements directly strengthen the adaptive capacity and resilience of local communities, particularly those dependent on forest and land resources for their livelihoods. By restoring ecosystem functionality and enhancing the provision of critical ecosystem services FLR significantly reduces the sensitivity of landscapes to climate extremes and provides a sustainable, long-term approach to climate change adaptation and environmental security.

4. Major Benefits of FLR for Climate Change Adaptation

Forest Landscape Restoration (FLR) provides multiple ecological, economic and social benefits that strengthen the adaptive capacity of both ecosystems and human communities against climate change. One of the most important benefits is biodiversity conservation (Holl, 2017), as FLR restores habitats for plants, animals, birds, insects and soil microorganisms, thereby improving habitat connectivity and supporting species migration under changing climatic conditions. This enhanced biodiversity strengthens ecosystem stability and resilience. FLR also contributes significantly to soil restoration by improving soil structure, increasing soil organic matter and reducing erosion caused by wind and water. Healthy soils enhance nutrient cycling, moisture retention and land productivity which are essential for sustainable agriculture and ecosystem functioning.

Another major benefit of FLR is improved water resource management. Restored forest landscapes enhance watershed health by increasing water infiltration, improving groundwater recharge and maintaining hydrological balance. This helps reduce flood risks during heavy rainfall while ensuring water availability during drought periods. Although FLR primarily supports adaptation it also contributes to carbon sequestration by capturing atmospheric carbon in tree biomass, roots and soils, thereby assisting in climate change mitigation by lowering greenhouse gas concentrations (IPCC, 2022). In addition, FLR supports livelihood improvement by generating employment opportunities in restoration activities and providing sustainable access to forest products, fodder, fuelwood and other income-generating resources for rural communities. Furthermore, restored landscapes play a critical role in disaster risk reduction by minimizing the impacts of landslides, floods, desertification and extreme climate events through improved ecological resilience and landscape stability.

5. FLR Strategies for Climate Change Adaptation

To achieve these benefits, several restoration strategies are commonly adopted in FLR programs, depending on landscape conditions and restoration goals. One widely used approach is natural regeneration, where degraded forests are allowed to recover naturally with minimal human intervention, enabling native species to re-establish ecological balance over time. In areas where natural recovery is slow assisted natural regeneration is applied by protecting regenerating vegetation through controlled grazing, invasive species management and supportive interventions to accelerate ecosystem recovery (Laestadius et al., 2015). Reforestation and afforestation are also important strategies involving tree plantation on degraded forest lands or non-forest areas to restore vegetation cover, improve carbon storage and enhance ecological stability.

Another highly effective strategy is the adoption of agroforestry systems (Food and Agriculture Organization, 2020), which integrate trees with crops and livestock to improve land productivity, diversify income sources and increase resilience to climate stress such as drought and heat. Agroforestry also strengthens soil fertility and microclimate regulation. Additionally, watershed restoration focuses on improving catchment areas through soil and water conservation measures, vegetation restoration and better water management practices to restore natural water flow and reduce land degradation. When implemented together in a coordinated manner, these FLR strategies help rebuild degraded landscapes, enhance ecosystem services and create climate-resilient landscapes capable of adapting to future environmental challenges.

6. Challenges in FLR Implementation

Despite its numerous benefits the implementation of Forest Landscape Restoration (FLR) faces several significant challenges that can limit its effectiveness and long-term sustainability. Limited financial resources, inadequate funding mechanisms and high restoration costs often restrict large-scale implementation particularly in developing regions. Poor policy coordination among government agencies and weak institutional frameworks may create delays in planning and execution. Land tenure conflicts and unclear ownership rights frequently discourage local participation and investment in restoration activities. In many cases, the lack of community awareness and participation further reduces restoration success as local stakeholders play a critical role in long-term management and protection of restored landscapes. Additionally, climate uncertainty, including prolonged droughts, heat waves, pest outbreaks and extreme weather events can negatively affect the survival and growth of planted species thereby slowing restoration progress. The selection of unsuitable species without considering local ecological conditions may also reduce restoration efficiency and ecosystem recovery. Furthermore, weak monitoring and evaluation systems limited access to modern restoration technologies and insufficient technical expertise can hinder proper assessment of restoration outcomes. Socio-economic pressures such as population growth agricultural expansion, overgrazing and unsustainable resource extraction also continue to exert pressure on restored landscapes. Addressing these challenges requires integrated policies, adequate funding, scientific planning, capacity building and strong stakeholder collaboration to ensure successful and sustainable FLR implementation.

7. Future Prospects

The future of Forest Landscape Restoration (FLR) is highly promising in the context of global climate change adaptation and sustainable ecosystem management. As climate-related challenges such as rising temperatures, prolonged droughts, floods and land degradation continue to intensify the need for large-scale landscape restoration is becoming increasingly important. Greater international investment in restoration programs along with stronger policy and institutional support can significantly accelerate FLR implementation across vulnerable regions. Global initiatives such as the United Nations Decade on Ecosystem Restoration highlight the importance of restoring degraded landscapes to enhance climate resilience, biodiversity conservation and sustainable development. To maximize the long-term effectiveness of FLR future efforts must focus on strengthening restoration policies that support coordinated planning and implementation at local, national and global levels (UNEP, 2021; Bonn Challenge, 2021). Promoting community-based restoration approaches is equally important as active participation of local communities ensures better resource management and long-term sustainability. The development of robust scientific monitoring systems is necessary to assess restoration progress, ecosystem recovery and adaptive outcomes under changing climate conditions. Furthermore, selecting climate-resilient tree and plant species will improve survival and restoration success under environmental stress. Integrating FLR into national climate adaptation plans and land-use strategies can further enhance its contribution toward building resilient landscapes and securing ecological and socio-economic sustainability for future generations.

8. Conclusion

Forest Landscape Restoration is a powerful and integrated approach for addressing climate change adaptation challenges. By restoring degraded landscapes enhancing biodiversity, improving soil and water resources and strengthening community resilience FLR provides long-term ecological and socio-economic benefits. Its ability to combine ecosystem restoration with livelihood improvement makes it an essential strategy for sustainable climate adaptation. Therefore, large-scale promotion of FLR can significantly contribute to resilient landscapes and a climate-secure future.

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Qureshi et al. (2026)

Chemotherapeutic Agents in Aquaculture Disease Management: Classification, Mechanisms, and Routes of Administration

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Abstract

The escalating demand for aquatic food products has driven the rapid intensification of aquaculture worldwide, simultaneously increasing the risk of infectious disease outbreaks caused by bacteria, fungi, viruses, and parasites. Chemotherapeutic intervention has become an indispensable component of disease management, playing a vital role in controlling infections and safeguarding aquaculture production. This review systematically classifies the principal groups of chemotherapeutic agents used in aquaculture, including antibacterials, antifungals, antiparasitic agents, antiviral compounds, anaesthetics, and disinfectants, with emphasis on their mechanisms of action, spectrum of activity, and practical applications in cultured fish and shellfish. The article also discusses the major routes of drug administration, including immersion, oral administration through medicated feed, injection, gavage, and topical application, highlighting their suitability according to disease type, fish size, and production system. Furthermore, it underscores the importance of the judicious use of chemotherapeutic agents to minimize the development of antimicrobial resistance (AMR), reduce drug residues in aquatic food products, and prevent environmental contamination. In addition, the article highlights emerging alternatives such as vaccines, probiotics, and immunostimulants as sustainable approaches for disease prevention and health management in aquaculture.

Keywords: Aquaculture, Chemotherapy, Antibiotics, Antifungals, Antiparasitic agents

1. Introduction

Global aquaculture production has expanded exponentially over recent decades, driven by declining wild catch fisheries and rising consumer demand for affordable, high-quality protein. Intensive culture practices involving high stocking densities and prolonged rearing cycles create conditions conducive to rapid pathogen transmission, opportunistic infections, and stress-mediated immune suppression in farmed species (Mishra et al., 2017). Bacterial diseases remain the dominant constraint, with pathogens such as *Aeromonas hydrophila*, Vibrio spp., Streptococcus spp., *Piscirickettsia salmonis*, and Flavobacterium spp. responsible for major production losses across species and regions (Noga, 2000). Viral diseases including Koi Herpesvirus (KHV), Viral Nervous Necrosis (VNN), Epizootic Haematopoietic Necrosis (EHNV), and Tilapia Lake Virus (TiLV) have emerged as serious threats, while fungal infections caused by Saprolegnia spp. and parasitic infestations (ectoparasites such as sea lice, Argulus, Lernaea, and various protozoa) compound the disease burden (Dinesh et al., 2023).

Chemotherapy - the application of chemical compounds to treat, prevent, or control disease has been a cornerstone of aquaculture health management (Treves-Brown, 2000). It operates on the principle of differential toxicity: the agent must be sufficiently toxic to the target pathogen at concentrations that do not cause significant harm to the host or the surrounding environment. Chemotherapeutic strategies may be prophylactic (preventive), metaphylactic (applied at the onset of a disease event in a population), or therapeutic (applied after confirmed diagnosis) (Singh and Singh, 2018). Each approach demands precise knowledge of drug pharmacokinetics, pathogen susceptibility, and system-specific parameters. This article provides a structured review of the major classes of chemotherapeutic agents used in aquaculture, their modes of action, and the methods by which they are administered to aquatic animal.

2. Classification of Chemotherapeutic Agents

2.1 Antibacterial Agents

Antibacterial agents constitute the largest and most commonly applied class of aquaculture therapeutants. They are employed both therapeutically to treat confirmed bacterial infections and prophylactically, particularly in intensive hatchery and grow-out systems. Their mechanisms of action can be grouped into three broad categories:

Table. 1 Major categories of chemotherapeutic agents used in aquaculture disease management

Drug Category	Key Examples	Target Pathogen	Mechanism of Action
Antibacterials	Oxytetracycline, Florfenicol, Erythromycin, Amoxicillin	Bacteria (Aeromonas, Vibrio, Streptococcus)	Inhibit cell wall, protein, or DNA synthesis
Antifungals	Malachite green, Bronopol (Pyceze), Sodium chloride	Saprolegnia, Aphanomyces	Oxidation of thiols; disruption of energy metabolism
Antiparasitic	Praziquantel, Ivermectin, Trichlorfon, Diflubenzuron	Monogeneans, Copepods, Crustacean ectoparasites	Neuromuscular disruption; chitin synthesis inhibition
Disinfectants	Formalin, Chloramine-T, Hydrogen peroxide, BKC	Broad spectrum (bacteria, viruses, fungi)	Protein denaturation; oxidative damage; membrane disruption
Antivirals	Limited; Chloramine-T (indirect)	Fish viruses (IPNV, VHSV, KHV)	Suppression of viral replication cycles
Anaesthetics	MS-222 (Tricaine), Benzocaine, Carbon dioxide	N/A (handling aid)	CNS depression; loss of equilibrium and reflex

- **Cell wall synthesis inhibition:** Beta-lactam antibiotics such as amoxicillin disrupt peptidoglycan cross-linking, causing osmotic lysis. Amoxicillin is effective against furunculosis caused by *Aeromonas salmonicida*.
- **Protein synthesis inhibition:** Tetracyclines (oxytetracycline) block ribosomal binding of aminoacyl-tRNA. Florfenicol (a phenicol antibiotic) and erythromycin (a macrolide) also act at the 50S ribosomal subunit, inhibiting translocation and peptide chain elongation respectively. Oxytetracycline has broad-spectrum activity against furunculosis, vibriosis, and Pseudomonas infections.
- **DNA replication inhibition:** Fluoroquinolones (enrofloxacin) and quinolones (oxolinic acid, flumequine) inhibit bacterial DNA gyrase and topoisomerase IV, preventing DNA uncoiling. They are effective against *Piscirickettsia salmonis* and gram-negative pathogens.

- **Folic acid synthesis inhibition:** Sulfonamides (sulfadiazine, sulfadimethoxine) and trimethoprim act synergistically to block sequential steps in folic acid biosynthesis. The combination Tribrissen (sulfadiazine:trimethoprim, 5:1) is used against furunculosis and vibriosis in salmonids.

Chloramphenicol, once widely used, is now banned for extra-label use in food-producing animals in many countries due to its association with aplastic anaemia and carcinogenic potential in humans (Sapkota et al., 2008). Nitrofurans, including furazolidone, are also prohibited globally in food-fish production (USFDA, 2021).

2.2 Antifungal Agents

Fungal infections, particularly Saprolegniasis caused by *Saprolegnia parasitica*, affect salmonid eggs and juveniles and can cause significant losses in hatcheries. Key antifungal agents include:

- **Malachite green:** A triphenylmethane dye historically used as both a fungicide and ectoparasiticide. It acts as a respiratory toxin by disrupting mitochondrial electron transport. Although highly effective, malachite green is now banned in food-fish aquaculture in the EU, USA, and India due to its mutagenic and potentially carcinogenic metabolites (Sapkota et al., 2008).
- **Bronopol (Pyceze):** A safer alternative to malachite green and formalin, bronopol exerts its antifungal effect through dual mechanisms — catalytic oxidation of available thiols (inhibiting fungal growth) and production of free radicals (causing cell death). It is approved for use in several countries.
- **Formalin:** Used as an antifungal bath treatment for salmonid eggs at concentrations of 500-1000 mg/L for 15 minutes. Formalin acts by crosslinking proteins and nucleic acids, disrupting both structure and function.
- **Sodium chloride:** Considered an eco-friendly antifungal; effective during egg incubation in freshwater finfish hatcheries. It alters the osmotic gradient between the fungus and the aquatic environment.
- **Hydrogen peroxide:** Active against Saprolegnia; approved in several jurisdictions including the USA (35% PEROX-AID) for treatment of saprolegniasis in freshwater-reared salmonids and channel catfish (USFDA, 2021). It has low environmental persistence.

2.3 Antiparasitic Agents

Parasitic infestations including those caused by ectoparasitic protozoa (*Ichthyophthirius, Trichodina*), monogenean trematodes (Gyrodactylus, Dactylogyrus), crustaceans (*Lepeophtheirus, Argulus, Lernaea*), and endoparasitic helminths — represent a significant production challenge. Treatment agents include:

- **Organophosphates (Trichlorfon, Dichlorvos/Nuvan):** Inhibit acetylcholinesterase, causing neuromuscular paralysis in crustacean ectoparasites. Used against sea lice (*Lepeophtheirus salmonis*), fish lice (*Argulus* spp.), and anchor worm (*Lernaea* spp.) via bath treatment.
- **Pyrethroids (Cypermethrin, Deltamethrin):** Interfere with voltage-gated sodium channels in nerve membranes, causing repetitive nerve firing and paralysis. Administered by bath for sea lice control in marine salmonids.
- **Avermectins (Emamectin benzoate/SLICE, Ivermectin):** Open glutamate-gated chloride channels in invertebrate inhibitory neurotransmitter synapses, causing hyperpolarization and paralysis. Emamectin benzoate is the only avermectin with market authorization for aquaculture use (medicated feed for sea lice control) (USFDA, 2021).
- **Chitin synthesis inhibitors (Diflubenzuron, Teflubenzuron):** Block chitin synthesis during moulting, preventing exoskeleton formation in larval and pre-adult sea lice. Administered as medicated feed additives.
- **Praziquantel:** An isoquinoline compound effective against monogenean, digenean (trematode), and cestode (tapeworm) infections. It impairs neuromuscular function in the parasite, disrupting suckers and hooks, and alters integument permeability.
- **Potassium permanganate ($KMnO_4$):** Broad-spectrum oxidant; used against protozoan and bacterial ectoparasites on skin and gills. It generates reactive oxygen that destroys cell walls and disrupts respiratory structures of parasites.
- **Hydrogen peroxide:** Used as an ectoparasiticide via bath treatment; causes mechanical paralysis through gas bubble formation in haemolymph and oxidative damage to parasite membranes.
- **Formalin:** Used as an external parasiticide against protozoa and monogeneans. FDA-approved at 15-25 µL/L for 1-hour immersion in finfish (USFDA, 2021).

2.4 Antiseptics and Disinfectants

Disinfectants are used to reduce pathogen loads in water, equipment, hatchery facilities, and on egg surfaces. Unlike antibiotics, which typically have specific intracellular targets, disinfectants act on multiple cellular components and have broader spectra of activity. Key agents include:

- **Chlorine compounds:** Chloramine-T releases hypochlorous acid in water, which enters bacterial cells, prevents enzymatic activity, and causes cell death. Effective as an antiviral and antibacterial agent, particularly for hatchery water treatment.
- **Formalin:** Broad-spectrum disinfectant effective against bacteria, viruses, fungi, and parasites. Acts by crosslinking proteins and nucleic acids. Despite being a known human carcinogen (IARC), it remains FDA-approved for aquaculture use due to limited alternatives (Sapkota et al., 2008; USFDA, 2021).
- **Hydrogen peroxide:** Acts as an antifungal, antibacterial, and antiviral compound; degrades rapidly in the environment making it an ecologically preferable option. Approved by the US FDA under the trade name 35% PEROX-AID (USFDA, 2021).
- **Iodophors (Povidone iodine):** Release free iodine which kills pathogens through destruction of proteins (particularly cysteine and methionine residues), nucleotides, and fatty acids. Used as egg surface disinfectants.
- **Benzalkonium chloride (BKC):** A quaternary ammonium compound; disrupts cell membrane permeability by interacting with phospholipids and proteins at the C12-C16 carbon chain positions. Effective against gram-positive bacteria and biofilm formation on gill surfaces.
- **Potassium permanganate:** Oxidizes organic material and cell walls of pathogens; used in hatchery disinfection and treatment of bacterial/fungal infections on skin and gills.
- **Virkon (Potassium peroxymonosulphate):** A broad-spectrum disinfectant used for equipment and facility sterilization.
- **Ozone and UV light:** Physical/chemical disinfection methods used in recirculating aquaculture systems (RAS) for pathogen reduction in incoming and outgoing water.

2.5 Antiviral Agents

Antiviral chemotherapy in aquaculture remains limited due to the fundamental challenge that viral replication is tightly coupled with normal host cell metabolism, making it difficult to suppress the virus without damaging the host (Treves-Brown, 2000). Unlike terrestrial medicine, no antiviral drugs are currently approved specifically for aquaculture use. Chloramine-T has been shown to reduce fish mortality from viral infections (IPNV, VHSV) through its disinfectant properties in water (Dinesh et al., 2023). The primary strategy for viral disease management remains prevention through vaccination, biosecurity, and enhanced innate immunity via immunostimulants and probiotics.

3. Routes of Drug Administration

The route of administration is determined by the nature and severity of the disease, the drug's physicochemical properties, the target fish species and life stage, and the production system (Singh and Singh, 2018). Table 2 summarizes the principal administration routes:

Table 2 Drug administration routes in aquaculture with methods, suitable applications, and limitations

Route	Method	Suitable For	Limitations
Immersion (Bath)	Prolonged bath, dip, or flush; drug added directly to culture water	Ectoparasites, external bacterial/fungal infections; small fishes and eggs	Requires water flow cessation; uniform distribution critical
Oral (Medicated Feed)	Drug mixed with feed (top-dressed or incorporated by feed mill)	Systemic diseases; large populations	Ineffective if fish are anorexic; proper storage required
Injection (IM/IP)	Intramuscular (dorsal musculature) or intraperitoneal (near pelvic fins)	High-value broodstock; small populations	Labour intensive; risk of internal organ damage
Gavage	Stomach tube attached to syringe; drug pumped into stomach	Experimental/research settings for precise dosing	Requires anaesthesia; stressful; rarely used commercially
Topical	Oil-based drug applied directly to skin lesion	Skin ulcers in high-value fish	Requires anaesthesia; very limited application

3.1 Immersion Treatment

Immersion is the most widely applicable and practical route for treating aquatic animals. The drug is dissolved directly in the culture water and administered as a prolonged bath (water flow stopped for a defined period), an indefinite bath (low concentration maintained over an extended period), a dip (high concentration for very brief exposure, typically under a minute), or a flush (drug solution added at inflow and allowed to pass through). Drugs of low molecular weight are preferred as they distribute uniformly through water and are absorbed efficiently via the gill epithelium, skin, and mucosa. Adequate aeration during treatment is essential, especially when water flow is interrupted.

3.2 Oral (Medicated Feed)

Medicated feed is the standard route for treating systemic infections in large fish populations. The drug is incorporated into the feed either as a top dressing (mixed with oil or gelatine and allowed to dry) or produced by licensed commercial feed mills. The major limitation is that diseased fish often exhibit reduced appetite, meaning treatment must begin before anorexia sets in to ensure adequate drug intake. Medicated feeds must be stored properly (cool, dry conditions) and used before expiry. Florfenicol, oxytetracycline, and sulfadimethoxine/ormetoprim are commonly administered via medicated feed.

3.3 Injection Treatment

Injection - intramuscular (IM) or intraperitoneal (IP) - provides the most predictable and measurable dose but is labour-intensive and stressful to fish. It is reserved for high-value individuals such as broodstock or for vaccine administration. IM injections are administered in the dorsal musculature at approximately 0.5-1.0 cm depth at a 45° angle; IP injections are given near the base of the pelvic fins, directing the needle along the body axis to avoid internal organs.

3.4 Gavage and Topical Application

Gavage involves passing a stomach tube attached to a syringe directly into the fish's stomach, ensuring precise dosage delivery. This method requires anaesthesia and is confined to experimental research settings. Topical application of oil-based drugs is used for wound treatment in high-value fish; anaesthesia is also required.

4. Antimicrobial Resistance and Emerging Alternatives

The indiscriminate and prophylactic use of antibiotics in aquaculture has contributed substantially to the emergence of antimicrobial-resistant (AMR) strains of fish pathogens, with significant implications for public health (Sapkota et al., 2008). Residues of antibiotics such as oxytetracycline, sulfonamides, and fluoroquinolones have been detected in fish flesh, sediments, and surrounding water bodies, creating reservoirs of resistance determinants (Burridge et al., 2010). Chlorine-based disinfectants have also been implicated in the advancement of multiple antibiotic resistance genes in bacteria.

In response, several alternative strategies have gained traction in sustainable aquaculture:

- **Vaccines:** The development of effective immersion, oral, and injectable vaccines have substantially reduced antibiotic use in salmonid aquaculture. Vaccines with pattern recognition receptor (PRR) ligands as adjuvants are being developed for improved efficacy.
- **Probiotics and prebiotics:** Beneficial microorganisms supplemented in feed or water to enhance gut microbiota diversity, immunity, and competitive exclusion of pathogens. Bacillus, Lactobacillus, and Saccharomyces species are commonly employed.
- **Immunostimulants:** Beta-glucans, nucleotides, and herbal extracts that enhance non-specific immune parameters including lysozyme activity, respiratory burst, and phagocytic activity.
- **Phage therapy:** Bacteriophages targeting specific fish pathogens offer highly specific, residue-free alternatives to broad-spectrum antibiotics.
- **Bio-remediators and water quality management:** Improved pond management, biosecurity, and probiotic-based water remediation reduce pathogen load and disease pressure, decreasing the need for chemotherapeutic intervention.

5. Conclusion

Chemotherapeutic agents remain an essential component of aquaculture health management, spanning antibacterials, antifungals, antiparasitic compounds, disinfectants, and anaesthetics. Each class operates through distinct mechanisms and requires careful selection based on pathogen identity, drug pharmacology, fish species, and production context. The route of administration immersion, medicated feed, injection, or topical further influences efficacy and must be matched to the disease presentation and operational feasibility. However, the escalating problem of antimicrobial resistance and environmental contamination demands that chemotherapy be used only when necessary, at appropriate doses, and ideally following laboratory-confirmed diagnosis. The integration of preventive strategies vaccines, probiotics, immunostimulants, and good aquaculture practices offers the most sustainable path forward for disease management in the global aquaculture industry.

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From Dams to Diversity: Managing Karnataka's Reservoir Fisheries

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Abstract

Karnataka possesses some of the most important inland fisheries resources in southern India due to its extensive network of reservoirs, rivers, tanks, and irrigation impoundments. Reservoir fisheries state contributes significantly to food security, employment generation, nutritional support, and rural livelihoods, particularly for economically weaker fishing communities. Major reservoirs such as Tungabhadra Reservoir, Krishna Raja Sagara, Almatti Dam, and Bhadra Reservoir support diverse fish populations including Indian major carps, catfishes, murrels, and several indigenous species. However, the sector faces numerous challenges, including overfishing, invasive exotic species, habitat degradation, pollution, irregular stocking practices, and weak cooperative management systems. Scientific stocking programs, conservation of native fishes, community participation, and sustainable reservoir governance can substantially improve fish productivity, biodiversity conservation in Karnataka. This article reviews the status, productivity, biodiversity, management practices, and conservation strategies associated with reservoir fisheries in Karnataka.

Keywords: Reservoir fisheries, Karnataka, Inland fisheries, Biodiversity, Fish production, Invasive species, Aquaculture

Introduction

India is among the leading inland fish-producing countries in the world, and reservoirs contribute significantly to this achievement (FAO, 2022; Ayyappan & Jena, 2001). Karnataka has a large number of major, medium, and minor reservoirs constructed primarily for irrigation, hydropower generation, and drinking water supply (Keshavanath & Gangadhara, 2012). Over time, these reservoirs have become important fisheries resources supporting thousands of fisherfolk families. Reservoir fisheries in Karnataka provide:

Employment opportunities, nutritional security, income generation & rural development support (Department of Fisheries, Government of Karnataka, 2024).

Geographic and Hydrological Profile of Karnataka Reservoirs

Karnataka has hundreds of reservoirs distributed across semi-arid plains, plateau regions, and Western Ghats (Department of Fisheries, Government of Karnataka, 2024). Important reservoirs include:

1. Tungabhadra Reservoir
2. Krishna Raja Sagara Reservoir
3. Almatti Dam
4. Bhadra Reservoir
5. Kabini Reservoir
6. Hemavathi Reservoir

These reservoirs differ in: Depth, water retention period, nutrient availability, productivity & fish diversity. Reservoirs located near the Western Ghats generally possess higher biodiversity due to favourable ecological conditions and perennial water availability (Bhat, 2003).

Fish Species Diversity and Ichthyofaunal Composition

Karnataka reservoirs support rich freshwater fish diversity comprising:

1. Indian Major Carps: Catla (*Catla catla*), Rohu (*Labeo rohita*) & Mrigal (*Cirrhinus mrigala*)
2. Minor carps
3. Catfishes
4. Murrels
5. Featherbacks
6. Freshwater prawns (Jhingran, 1988; Sugunan, 1995)

Catla (*Catla catla*) Rohu (*Labeo rohita*) Mrigal (*Cirrhinus mrigala*)

Several ecologically important native species have also been reported including:

Deccan Mahseer (Tor khudree) & Tor mussullah (Bhat, 2003).

The family Cyprinidae generally dominates reservoir fisheries in Karnataka (Sugunan, 1995). Fish assemblages vary depending on: reservoir age, water quality, stocking practices & hydrological conditions.

Impact of Reservoir Creation on Fish Composition

Construction of reservoirs significantly alters natural river ecosystems. Riverine fish species adapted to flowing water conditions gradually decline, while lentic-adapted species become dominant (Jhingran, 1988). Reservoir impoundment leads to habitat modification, changes in breeding grounds, altered migration patterns, and nutrient redistribution (Sugunan & Sinha, 2000). Stocking of Indian Major Carps has become a common management strategy in Karnataka reservoirs to enhance fish production (Dhanze & Dhanze, 2018).

Reservoir impoundment leads to: Habitat modification, changes in breeding grounds, altered migration patterns & nutrient redistribution. Stocking of Indian Major Carps has become a common management strategy in Karnataka reservoirs to enhance fish production.

Production Potential and Current Yields

Fish productivity in Karnataka reservoirs varies according to reservoir size and management efficiency (Sugunan, 1995). Small reservoirs generally show higher productivity per hectare, whereas large reservoirs contribute substantially to total fish production (Sugunan & Sinha, 2000). Culture-based fisheries are increasingly being promoted in medium and small reservoirs (Keshavanath & Gangadhara, 2012). The total freshwater area in Karnataka is approximately 5.74 lakh hectares, of which reservoirs account for 2.72 lakh hectares (Karnataka Fisheries Department, 2023).

Production Data (Latest Estimates)

Karnataka's total fish production reached 1,225,000 tonnes in 2023, compared to 1,074,000 tonnes in 2022 (Karnataka Fisheries Department, 2023). Inland fisheries are growing rapidly and contributing significantly to national fish production (FAO, 2022).

Key Reservoirs & Management

The state's reservoir fisheries are distributed across major river basins:

River System	Major Reservoirs
Krishna Basin	Narayanpur (Upper Krishna), Tungabhadra, Bhadra, Ghataprabha, Malaprabha, VV Sagar
Cauvery Basin	Hemavathy, Harangi, Kabini, Nugu, Manchanbele
Sharavathy	Linganamakki

Note on Yield: While Karnataka ranks 5th in India for freshwater area, it ranks 10th in actual freshwater production, indicating significant unfulfilled potential in its reservoirs.

Latest Infrastructure & Schemes (2026 Updates)

Under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), which has received a budgetary allocation of ₹2,500 crore for 2026-27, several initiatives are being scaled in reservoirs:

Cage Culture: As of March 2026, 52,058 reservoir cages have been approved nationwide to intensify production.

Modern Systems: A shift toward technology-driven aquaculture is evident with the approval of 12,081 RAS units and 4,205 Bio-floc units as of January 2026.

Support Systems: Livelihood support during fishing ban periods has benefited approximately 4.33 lakh fisher families as of early 2026.

Problems and Constraints in Reservoir Fisheries Management

1. Invasive Exotic Fish Species

Invasive fishes threaten native biodiversity and ecological balance in Karnataka reservoirs. Common invasive species include:

1.Tilapia (*Oreochromis mossambicus*)

2. African Catfish (*Clarias gariepinus*)

3. Common Carp (*Cyprinus carpio*)

These species compete with indigenous fishes for: Food, habitat & breeding areas (Sandilyan, 2022).

2. Overfishing and Illegal Fishing

Unregulated fishing practices, use of small mesh nets, juvenile fish capture, and poaching reduce fish stocks and breeding success. This exacerbated by a lack of strict enforcement, seasonal bans & coordinated monitoring (Dhanze & Dhanze, 2018).

3. Fish Seed Supply and Quality Issues

Many reservoirs suffer from an inadequate supply of quality fingerlings for stocking programs. Poor transportation, low survival rates, and inconsistent stocking density reduce fish production efficiency. Dependence on seed from neighboring states also creates logistical and quality-control problems.

4. Pollution and Habitat Degradation

Agricultural runoff, industrial discharge, domestic sewage, and eutrophication negatively affect reservoir ecosystems (FAO, 2022).

5. Declining water quality

Oxygen depletion, fish mortality, reduced breeding success & biodiversity loss.

Conservation Imperatives and Strategies

1. Protection of Native Species

Conservation of indigenous fishes such as Mahseer species is essential for maintaining ecological balance and biodiversity (Bhat, 2003).

Strategies include: hatchery development, broodstock conservation, habitat restoration & breeding ground protection.

2. Control of Invasive Species

Strict regulation of the introduction and release of exotic species into open waters is necessary. Management strategies include: awareness programs, monitoring systems, controlled aquaculture practices & legal enforcement.

3. Community-Based Co-Management

Reservoir fisheries can be managed effectively through the participation of fisher cooperatives, local communities, government agencies & research institutions.

4. Community-Based Fisheries Management

Community-based fisheries management improves sustainability and livelihood security (Sugunan & Sinha, 2000).

5. Policy and Institutional Support

Government schemes like PMMSY play a vital role in reservoir stocking, infrastructure development, and fisher welfare programs (Department of Fisheries, Government of Karnataka, 2024).

Support:

Reservoir stocking, fish seed production, Infrastructure development & fisher welfare programs.

Conclusion

Reservoir fisheries in Karnataka represent a valuable resource with significant potential for sustainable fish production, biodiversity conservation, and rural livelihood enhancement. Despite substantial opportunities, the sector faces challenges to invasive species, overfishing, habitat degradation, poor fish seed supply, and weak governance mechanisms. Scientific reservoir management, conservation-oriented fisheries policies, community participation, and improved stocking programs are essential for long-term sustainability. Strengthening institutional coordination and promoting ecosystem-based fisheries management can substantially enhance the ecological and economic benefits of Karnataka's reservoir fisheries.

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Precision Aquaculture: Redefining the Future of Fish Farming

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Abstract

Aquaculture has become a cornerstone of global food security, yet its rapid intensification has created significant challenges related to disease management, environmental sustainability, and resource-use efficiency. Precision aquaculture has emerged as an innovative approach that integrates advanced technologies, including the Internet of Things, artificial intelligence, machine learning, biosensors, and automated monitoring systems, to optimize aquaculture production. By enabling real-time monitoring of environmental conditions, fish behaviour, and health status, precision technologies facilitate data-driven decision-making and predictive management strategies. These tools improve feed efficiency, enhance disease detection, reduce environmental impacts, and promote animal welfare, thereby increasing the productivity and resilience of aquaculture systems. Furthermore, precision aquaculture offers promising solutions for adapting to climate-related challenges and supporting sustainable intensification of fish farming. As digital technologies continue to advance, precision aquaculture is poised to transform conventional fish farming into an intelligent, efficient, and environmentally responsible production system for the future.

Keywords: Fish, Food, Sustainable aquaculture, Sensors

Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors in the world and presently contributes more than half of the aquatic food consumed globally. As demand for high-quality animal protein increases, unprecedented pressure is expected to be placed on food production systems. Capture fisheries have reached or exceeded their sustainable limits in many regions, making aquaculture an indispensable component of future food and nutritional security (Ubina and Cheng, 2022). However, the rapid expansion and intensification of aquaculture have also brought several challenges, including disease outbreaks, increasing feed costs, environmental degradation, climate change, and concerns regarding sustainability.

Conventional aquaculture management practices largely rely on periodic observations and experience-based decision-making. Farmers typically monitor water quality manually, assess fish behaviour through visual inspection, and implement corrective measures only after problems become apparent. Such approaches are increasingly inadequate in modern intensive production systems, where environmental conditions can change rapidly and even minor disturbances may result in significant economic losses. Consequently, there is a growing need for innovative technologies capable of improving production efficiency while ensuring environmental and economic sustainability (Antonucci and Costa, 2019).

Precision Aquaculture: A New Paradigm in Fish Farming

The concept of precision aquaculture has emerged as a transformative approach to address these challenges. Derived from the principles of precision agriculture, precision aquaculture refers to the application of advanced technologies for real-time monitoring, analysis, and management of aquaculture systems. It aims to provide the right intervention at the right time and in the right quantity by integrating biological, environmental, and production data into management decisions (Antonucci and Costa, 2019). Precision aquaculture represents a fundamental shift from reactive management to predictive and preventive management. Rather than responding to problems after they occur, farmers can anticipate changes in environmental conditions, fish health, and production performance, thereby improving operational efficiency and minimizing risks. The approach integrates a wide range of technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine learning, remote sensing, computer vision, biosensors, robotics, and cloud computing (Fore et al., 2018). Together, these technologies form the basis of intelligent aquaculture systems capable of continuous monitoring and automated decision-making (Wang et al., 2021).

Real-Time Environmental Monitoring

Water quality is one of the most important determinants of fish health and productivity. Parameters such as temperature, dissolved oxygen, pH, salinity, ammonia, and turbidity directly influence metabolism, growth, feed utilization, and disease susceptibility (Wang et al., 2021). In conventional farming systems, these parameters are often measured intermittently, making it difficult to detect rapid environmental fluctuations. The development of sensor technologies has revolutionized environmental monitoring in aquaculture. Modern farms are increasingly equipped with sensor networks that continuously measure critical water quality parameters and transmit information in real time to centralized databases or mobile applications. Continuous monitoring offers several advantages. For example, sudden reductions in dissolved oxygen can be detected before they become critical, allowing farmers to activate aerators and prevent mortality events. Similarly, real-time monitoring of ammonia and temperature can facilitate timely interventions that reduce stress and improve fish welfare. The ability to monitor environmental conditions continuously and remotely has significantly improved farm management efficiency and reduced production risks (Antonucci and Costa, 2019).

Artificial Intelligence and Data-Driven Decision Making

The increasing availability of large datasets has created opportunities to integrate artificial intelligence and machine learning into aquaculture management. These technologies can process enormous volumes of information and identify patterns that may not be readily apparent through conventional observations (Huang and Khabusi, 2025). Machine learning algorithms can be used to predict growth rates, estimate biomass, optimize stocking densities, and forecast harvest times. Predictive models can also identify environmental conditions associated with disease outbreaks or poor production performance, enabling proactive management interventions. Artificial intelligence is increasingly being used to develop decision-support systems that assist farmers in making informed management decisions. By converting complex datasets into actionable information, AI has the potential to significantly improve production efficiency and reduce operational uncertainties (Wang et al., 2021).

Precision Feeding and Nutritional Management

Feed represents the largest operational expense in aquaculture and may account for more than half of total production costs. Inefficient feeding practices not only increase production costs but also contribute to environmental pollution through nutrient loading and organic waste accumulation. Precision feeding technologies have emerged as important tools for improving feed management. Underwater cameras, acoustic sensors, and computer vision systems can continuously monitor fish behaviour and feeding activity. Artificial intelligence algorithms analyse these behavioural responses and determine the optimal timing and quantity of feed delivery. Automated feeding systems can subsequently adjust feeding rates according to appetite, environmental conditions, and biomass estimates. Such approaches improve feed conversion efficiency, reduce feed wastage, and minimize nutrient discharge into the environment. Precision feeding therefore contributes not only to economic profitability but also to environmental sustainability (Huang and Khabusi, 2025; Zhou et al., 2018).

Precision Health Management and Disease Detection

Disease outbreaks remain one of the most significant constraints to global aquaculture production and are responsible for billions of dollars in economic losses annually. Traditional disease management strategies are largely reactive and frequently rely on treatments after clinical signs have become evident. Precision aquaculture offers opportunities to transform disease management from reactive to predictive approaches. Computer vision technologies can identify subtle alterations in swimming behaviour, feeding activity, and respiratory patterns that often precede disease outbreaks. Biosensors capable of detecting physiological stress indicators and specific pathogens are also being developed for real-time health monitoring. Early detection of health disturbances enables timely interventions, reduces mortality, and decreases the need for therapeutic treatments, including antibiotics (Huang and Khabusi, 2025). Such approaches are particularly important in the context of increasing concerns regarding antimicrobial resistance and sustainable aquaculture practices.

Challenges and Future Perspectives

Despite its enormous potential, the widespread adoption of precision aquaculture faces several challenges. The initial investment required for advanced technologies may be prohibitive for many small-scale producers, particularly in developing countries. Furthermore, successful implementation requires technical expertise in data management, sensor maintenance, and interpretation of analytical outputs. Issues related to data standardization, interoperability of technologies, and cybersecurity also require attention. In addition, there remains a need for cost-effective technologies that can be adapted to diverse farming systems and species. Nevertheless, advances in artificial intelligence, cloud computing, robotics, genomics, digital twins, and biosensor technologies are expected to accelerate the development of intelligent aquaculture systems. Future farms may become increasingly autonomous, capable of self-monitoring, self-learning, and self-optimising.

Conclusion

Precision aquaculture represents a paradigm shift in the management of aquaculture production systems. By integrating digital technologies with biological and environmental monitoring, it offers opportunities to improve productivity, optimize resource utilization, enhance animal welfare, and reduce environmental impacts. As the global demand for aquatic food continues to rise, the adoption of precision technologies will become increasingly important for ensuring the sustainability and resilience of aquaculture. The future of fish farming is likely to be data-driven, predictive, and highly automated. In this emerging era of intelligent aquaculture, precision technologies will not simply support aquaculture production—they will fundamentally redefine the way aquatic food is produced in the twenty-first century.

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Aquatic Plants: The Unsung Heroes of Water Quality Management

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Abstract

Aquatic plants are vital for improving water quality and promoting sustainable aquatic ecosystem management through natural phytoremediation. The present article summarizes the roles of emergent, floating, and submerged macrophytes in removing excess nutrients, trapping suspended solids, enhancing dissolved oxygen, supporting beneficial microorganisms, and sequestering heavy metals. Species such as *Eichhornia crassipes*, *Pistia stratiotes*, *Ipomoea aquatica*, *Lemna* spp., and *Azolla* spp. effectively reduce pollutants from aquaculture effluents and wastewater. Their integration into aquaculture systems improves water quality, lowers disease risks and operational costs, and produces valuable biomass for feed, fertilizer, and bioenergy. The article also highlights their application in Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA), emphasizing careful species management to maximize environmental sustainability and support the blue economy.

Keywords: Aquatic plants, Integrated Multi-Trophic Aquaculture, Phytoremediation, Sustainable aquaculture, Water quality management

1. Introduction

Beneath the surface of every healthy pond, river, and mangrove lies a silent cleaning crew. Aquatic plants - *hydrophytes* - aren't just scenery. They are nature's most understated engineers, evolved to do what chemicals and machinery often cannot: keep water alive. For years, we have leaned on fertilizers, industrial discharge controls, and high-tech interventions to manage nitrates and phosphates in our waterways. Yet contamination keeps climbing - from aquaculture effluent, agricultural runoff, and urban waste. The result is collapsing fish stocks, vanishing biodiversity, and growing risks to human health. Clean water is no longer a local concern; it is a global emergency. Long before treatment plants existed, waterways already knew how to clean themselves. Aquatic plants act as living biofilters, sucking up the same excess nitrogen and phosphorus that fuel toxic algal blooms. Their roots host thriving colonies of beneficial bacteria that break down organic waste and neutralize harmful compounds - no power grid required. And the numbers are striking. In controlled aquarium trials, for instance, tanks with *Najas guadalupensis* held nitrate levels at just 8.75–11.50 mg/L by week four, compared to 33.75–35.00 mg/L in untreated tanks - a roughly 70% reduction (Csontos et al., 2024). Phosphate levels tell a similar story, dropping from around 2.4 mg/L to barely above 1 mg/L (Csontos et al., 2024). In fishponds planted with water spinach (*Ipomoea aquatica*), researchers documented 30.6% removal of total nitrogen and 18.2% removal of total phosphorus after just 120 days (Li & Li, 2009).

Beyond nutrients, certain species pull heavy metals - lead, copper, chromium, cadmium - directly out of the water column through their roots and tissues, effectively detoxifying industrial and municipal wastewater without a single chemical input (Kumar, 2009). During daylight, these plants photosynthesize, releasing oxygen into the water and absorbing carbon dioxide. That simple act stabilizes pH and raises dissolved oxygen levels - two of the most important indicators of water health. Their stems and leaves also trap suspended sediments, clearing turbidity and letting sunlight reach deeper waters. The side effects of clean water, it turns out, are themselves more clean water.

The world is searching for sustainable, low-cost ways to manage pollution, and aquatic plants offer something rare: a solution that is effective, regenerative, and self-replicating. They clean the water, shelter aquatic life, and ask for nothing more than the right conditions to thrive. The next time you spot water hyacinths bobbing on a pond or reeds fringing a riverbank, look closer. They aren't decoration. They are working - quietly, endlessly, and without a single invoice - to keep the ecosystem alive.

2. The Triple-Action Cleaners: How Aquatic Plants Purify Water

Aquatic plants aren't passive decoration on the water's surface. They are extraordinarily efficient natural biofilters, quietly running three integrated processes at once: soaking up nutrients, pumping out oxygen, and trapping pollutants - all while hosting thriving microbial communities on their roots.

2.1 The Nutrient Sponge

Scientists call it *phytoremediation* - from the Greek *phyto* (plant) and the Latin *remedium* (to restore) - and it is, in many ways, the original water treatment. Aquaculture ponds, for instance, are notorious for accumulating nitrogen and phosphate from uneaten feed, fish waste, and decomposing organic matter. Aquatic plants absorb that surplus before it can fuel the algal blooms that smother ponds and kill fish.

The numbers are hard to argue with. A controlled Malaysian study using five common aquatic plants to clean aquaculture wastewater recorded phosphate removal rates as high as 98% with water hyacinth (*Eichhornia crassipes*) and total suspended solids down by up to 98% with water lettuce (*Pistia stratiotes*) (Nizam et al., 2020).

2.2 Keeping Water Clear and Balanced

Those same plants do far more than suck up chemicals. Their dense root systems act like nets, capturing suspended particles and sediments and leaving the water visibly clearer. Beneath the surface, those roots create a perfect habitat for beneficial bacteria that break down organic waste and convert toxic compounds into less harmful forms (Fig.1).

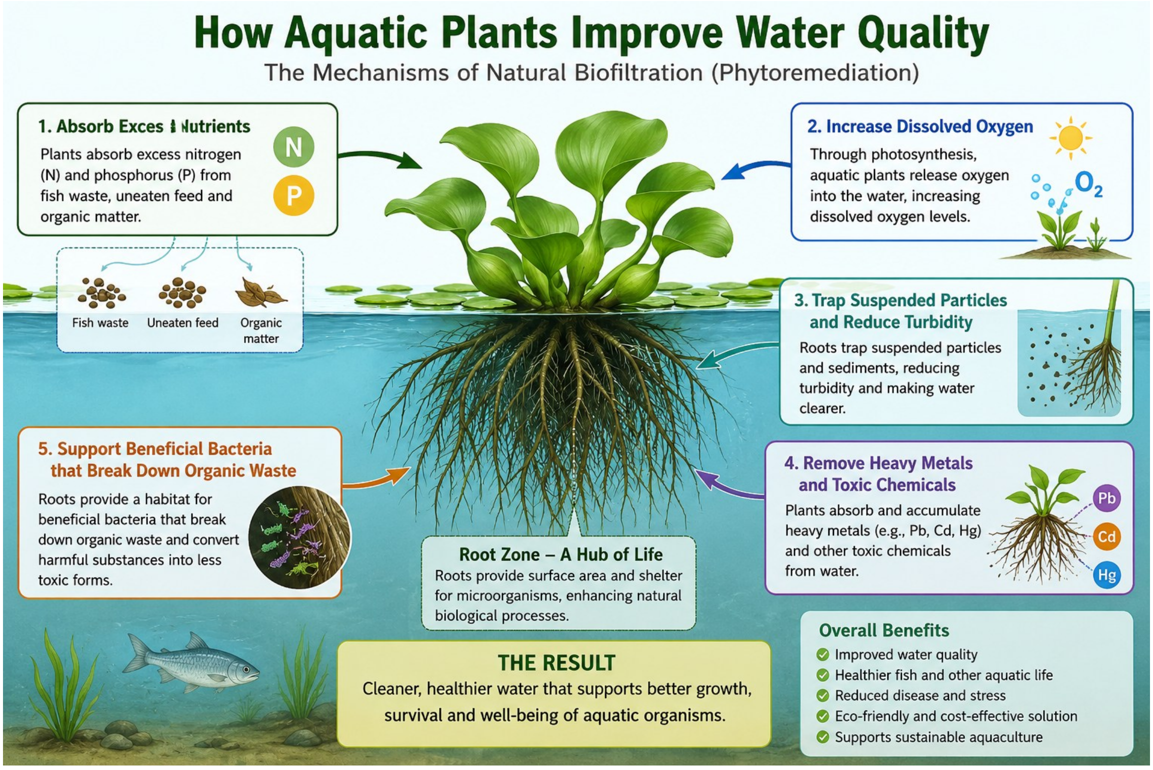

Fig. 1 Use of aquatic plants to improve water quality

During daylight, the plants photosynthesize - releasing oxygen into the water and pulling carbon dioxide out - which stabilizes pH and lifts dissolved oxygen levels. A review of the field confirmed that *Salvinia molesta* and *Pistia stratiotes* are particularly effective at this kind of biological water treatment, owing to their fast growth, resilience in toxic conditions, and high bioaccumulation potential (Mustafa & Hayder, 2020).

2.3 Heavy-Metal Stabilizers

Aquatic plants are also quietly tackling one of the most stubborn pollution problems on Earth: heavy metals. Species like duckweed, water hyacinth, and water lettuce can absorb - and store - toxic elements such as lead, cadmium, mercury, and arsenic in their tissues, drawing them out of the water column. A controlled Vietnamese study found that water hyacinth removed between 59% and 92% of cadmium, arsenic, lead, zinc, and copper from industrial wastewater within just 30 days, bringing concentrations back within safe discharge limits (Huynh et al., 2021). Another study using the same species showed removal rates above 80% for lead, copper, cadmium, and arsenic at concentrations as high as 8 mg/L (Peng et al., 2020). The bonus? The harvested plant biomass can sometimes be put to further use - turned into biogas, compost, or other products - turning a remediation project into a circular one.

3. The Three Eco-Zones of a Healthy Shoreline

Step to the edge of any healthy lake, pond, or estuary, and you'll find three distinct plant communities doing three very different jobs - a shoreline guard, a surface shader, and a deep-water workhorse. Together they form one of nature's most elegant partnerships.

3.1 The Shoreline Guard

These are the sentinels. Rooted in shallow water but rising proudly above the surface, emergent plants like cattails (*Typha spp*.) and reeds (*Phragmites australis*) act as living fences. They slow down incoming runoff, filter out silt, trash, and fertilizer before any of it reaches open water, and their dense stems blunt the force of waves and erosion. They are the first line of defense - ecologically and literally.

3.2 The Surface Shaders

Free-floating species drift at the water's skin, unanchored to the bottom. They range from barely-there specks like duckweed (*Lemna spp*.) and azolla (*Azolla spp*.) to showy mats of water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*), whose rosettes can stretch a foot across. Their leaves shade the water below, cooling it and suppressing the sunlight that fuels unwanted algal growth. And for all their beauty, some - like water hyacinth - are also remarkably efficient at pulling nutrients and even heavy metals from the water column, with documented removal rates exceeding 80–90% for several common contaminants (Huynh et al., 2021; Nizam et al., 2020).

3.3 The Deep-Water Workhorses

Fully underwater and often out of sight, submerged species like hydrilla (*Hydrilla verticillata*), hornwort (*Ceratophyllum demersum*), and eelgrass (*Zostera marina*) are the oxygen factories of the system. They release dissolved oxygen into the water all day, anchor sediments with their roots, and create the tangled cover where juvenile fish can hide from predators. Without them, the deeper layers of any waterbody can quickly become lifeless.

Table 1 Different types of aquatic weeds

Floating	**Submerged**	**Emergent**
Water hyacinth (*Eichhornia crassipes*)	Hydrilla (*Hydrilla verticillata*)	Reeds (*Phragmites australis*)
Duckweed (*Lemna spp.*)	Hornwort (*Ceratophyllum demersum*)	Cattails (*Typha spp.*)
Azolla (*Azolla spp.*)	Eelgrass (*Zostera marina*)	Water lettuce (*Pistia stratiotes*)

The point isn't simply to know these categories - it's to appreciate that removing any one of them breaks the system. A shoreline without emergent leaks sediment. A surface without floaters overheats and blooms. A water column without submerged plants suffocates. Healthy water isn't an accident. It's a stack of three living layers, breathing together.

4. Benefits of Aquatic Plants in Aquaculture

For most of the modern aquaculture era, clean water has meant costly infrastructure - aeration systems, mechanical filters, chemical treatments, frequent water exchanges. There's a quieter revolution underway. Instead of fighting nature with machinery, smart farmers are starting to work with it. Aquatic plants in and around grow-out ponds are now recognized as some of the most cost-effective tools available for keeping fish healthy and ponds productive. They pull surplus nutrients from the water, trap sediment, oxygenate during daylight, and create refuge for the microbes that finish the breakdown of organic waste. The difference shows up quickly in growth, survival, and feed-conversion performance.

4.1 Cleaner Water, Healthier Fish

In a Chinese carp-pond trial, simply floating vegetables like water spinach on one-sixth of the pond surface removed 30.6% of total nitrogen and 18.2% of total phosphorus from the system over four months - while unplanted control ponds saw those same nutrients accumulate (Li & Li, 2009). Cleaner water means lower stress on the fish, fewer disease outbreaks, and ultimately, better yields.

4.2 Tiny Biochemical Shields

Several aquatic species also produce alkaloids, tannins, and terpenoids - secondary metabolites that damage the cell membranes of pathogenic bacteria and fungi. Cattails and water hyacinths have shown the ability to physically filter waterborne pathogens like *E. coli* and release antimicrobial exudates into the surrounding water, turning the farm itself into a kind of biological sanitizer. The antioxidant power of some of these compounds exceeds that of vitamin C - the suppression isn't marginal, it's significant.

4.3 Lower Farming Costs

Once established, aquatic plants keep working without electricity or operator input. Mechanical aerators, routine chemical treatments, and the constant chore of water exchange can be reduced or eliminated in well-planted systems - an obvious win for smallholders operating on thin margins.

4.4 An Extra Harvest from the Same Pond

Some plants pay back twice. Azolla and duckweed are protein powerhouses - duckweed carries 20–35% crude protein, Azolla 15–40%, with doubling times as fast as 16–48 hours for some duckweed species. At modest inclusion rates (around 2.5–5% of the diet), both have shown measurable improvements in growth rate, protein efficiency, and feed conversion in carp and other omnivorous fish (Kamil & Taha, 2022; Minich & Michael, 2024). Surplus biomass can be composted, fed to poultry, or used as organic fertilizer - turning a remediation by-product into a second income stream.

5. The Other Side of the Coin: When the Helpers Take Over

Not every aquatic plant stays where you put it. Water hyacinth is the cautionary tale of green technology gone wrong. Under the right conditions, its doubling time can be measured in days, and dense mats can choke entire waterways (Mustafa & Hayder, 2020). The plant suffocates native species, blocks navigation and irrigation canals, raises water acidity, drops oxygen levels, and even creates breeding habitat for mosquitoes and snails carrying bilharzia. The same biological vigor that makes water hyacinth an exceptional purifier in a controlled pond makes it an ecological disaster in open water. The lesson is simple: choice of species, containment, and active management matter as much as the principle itself.

6. What's Next: Plant-Based Aquaculture at Industrial Scale

Two ideas are converging in modern aquaculture - and aquatic plants sit at the center of both. Recirculating Aquaculture Systems already recycle 90–99% of their water, but they depend on energy-hungry biofilters and constant monitoring (Fredricks, 2015). Adding a floating-plant module - duckweed, water lettuce - cuts nutrient loads before they hit the biofilter, raises dissolved oxygen, and lightens the system's energy footprint. In a Chinese floating-bed recirculating system, the plant ponds alone contributed to total nitrogen and total phosphorus removal rates of 69.6% and 77.9% respectively.

Integrated Multi-Trophic Aquaculture is the bolder innovation. Fish excrete ammonia and phosphate; aquatic plants absorb them and grow. A pilot duckweed-based IMTA system has demonstrated removal of 0.78 tonnes of total nitrogen and 0.38 tonnes of total phosphorus per year, while producing biomass with over 21% protein content (Paolacci et al., 2022). Theoretical models suggest marine IMTA systems can theoretically retain up to 79–94% of feed-derived nitrogen, phosphorus, and carbon if the species are carefully matched (Nederlof et al., 2021); realistic on-farm efficiencies still hover at 45–75%.

The future of aquaculture won't be decided only by bigger tanks or better feed (Fig.2). It will be decided by how cleverly farmers close the loop between fish, plants, and the water they share. Aquatic plants may be the cheapest, most versatile, and most underused tool we have to do exactly that.

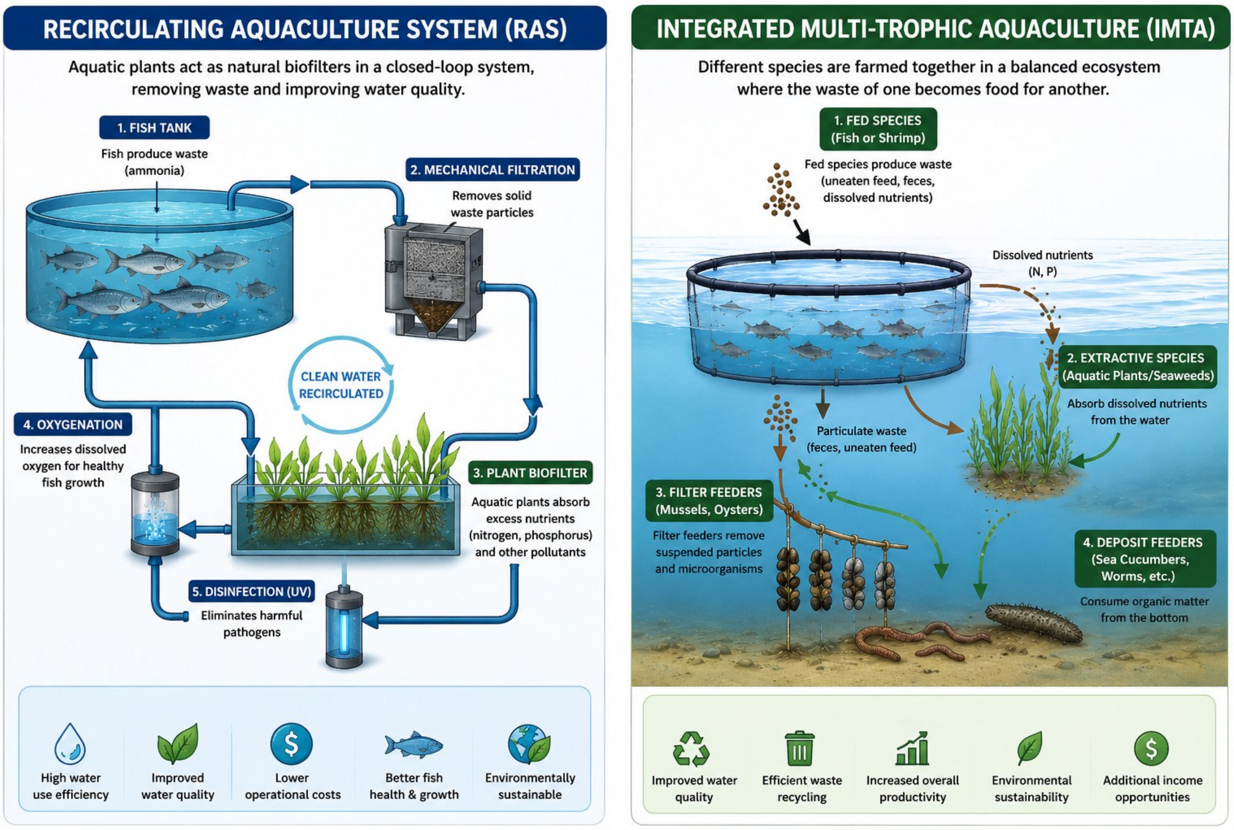

Fig. 2 Use of aquatic plants in RAS and IMTA system

7. Conclusion

Aquatic plants are among the most effective and sustainable natural tools for maintaining and restoring water quality in aquatic ecosystems. Through nutrient uptake, oxygen production, sediment trapping, and heavy metal sequestration, they function as living biofilters that improve water quality while supporting biodiversity and ecosystem stability. Their integration into aquaculture systems offers multiple benefits, including enhanced water quality, reduced disease risk, lower operational costs, and the generation of valuable biomass that can be utilized as feed, fertilizer, or bioenergy resources. Emergent, floating, and submerged aquatic plants each contribute unique ecological functions, collectively creating a balanced and resilient aquatic environment. However, successful application requires careful species selection and management to prevent ecological issues associated with invasive plants. As aquaculture moves toward resource-efficient and environmentally responsible production systems, the incorporation of aquatic plants into Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and wastewater treatment frameworks presents a promising pathway toward circular and sustainable blue economy practices. By harnessing the natural purification capacity of aquatic plants, future aquaculture and water management strategies can reduce environmental impacts, improve resource utilization, and contribute significantly to long-term ecosystem health and food security.

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Lessons from the Mothers' Market: What the Rest of India Can Learn from Manipur

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Abstract

The Mothers' Market (Ima Keithel) of Manipur represents one of the world's oldest and largest women-managed marketplaces and stands as a remarkable example of women-led development. For more than five centuries, the market has served not only as a centre of trade but also as a platform for entrepreneurship, financial inclusion, social capital formation, and cultural preservation. This article examines the unique features of Ima Keithel and explores the lessons it offers for promoting inclusive and sustainable development across India. Despite challenges, the resilience of women vendors continues to sustain the institution. The experience of Ima Keithel highlights the importance of women-led enterprises, financial inclusion, local entrepreneurship, and community-based development in achieving long-term socio-economic transformation.

Keywords: Women entrepreneurship, Women-led development, Financial inclusion, Social capital

Introduction: A Market Rooted in History

Across India, governments and development agencies invest heavily in programmes aimed at women's empowerment, entrepreneurship, self-help groups, livelihood enhancement, and financial inclusion. Yet, in the north-eastern state of Manipur exists a remarkable institution that has practiced many of these principles successfully for more than five centuries. Known as Ima Keithel, or the Mothers' Market, this unique marketplace in Imphal is entirely run and managed by women. More than a centre of commerce, Ima Keithel is a living example of women's entrepreneurship, collective action, cultural preservation, and community-led development. With an estimated 3,000–5,000 women vendors and a history stretching back over 500 years, it stands as one of the world's largest and oldest women-managed markets. At a time when India is promoting "women-led development," the Mothers' Market offers powerful lessons that deserve national attention. The origins of Ima Keithel can be traced to the traditional *Lallup-Kaba* system, under which Manipuri men were often engaged in military and state duties. Women assumed responsibility for production, trade, and household management. Over generations, these economic activities evolved into organized women-led marketplaces that became central to the state's economy and society.

Women as Economic Leaders: A Living University of Entrepreneurship

The women vendors of Ima Keithel represent a diverse yet resilient entrepreneurial community. Most vendors operate self-owned enterprises and rely on a combination of personal savings, Marup savings groups, informal credit sources, and microfinance institutions to finance their business activities. Their earnings contribute substantially to household welfare, often serving as a major source of family income. Educational attainment among vendors varies widely, ranging from informal education to graduate-level qualifications. One of the most striking features of Ima Keithel is the remarkable diversity of products traded by women vendors. The market serves as a major source of vegetables and fruits, contributing significantly to urban food security and nutrition, while the trade in fish and meat products supports local value chains and livelihoods. Traditional handlooms and textiles not only generate employment but also help preserve Manipur's rich cultural heritage. Similarly, the sale of handicrafts and bamboo products provides important non-farm employment opportunities for rural households. The market is also renowned for its traditional foods, which attract tourists and strengthen the cultural identity of the region.

Beyond Livelihoods: Building Human Capital

A key factor behind the success and resilience of Ima Keithel is the strong network of social institutions that support women vendors. Vendor associations offer collective representation and help address common concerns affecting traders, while extensive peer networks facilitate the exchange of market information, business experiences, and practical knowledge. The market also functions within a framework of shared community norms that promote trust, accountability, and cooperation among vendors. In times of difficulty, women benefit from various informal support systems that provide mutual aid and help manage economic and social risks**.** The success of Ima Keithel cannot be explained by physical infrastructure alone. The market thrives because of strong social capital built on trust, cooperation, and collective action. Women vendors support one another through informal networks and traditional financial institutions such as Marup, a rotating savings and credit system that has operated for generations.

Markets as Social Institutions

Unlike conventional marketplaces that focus solely on commerce, Ima Keithel functions as a social institution. Researchers have observed that women frequently describe the market as a family and a community rather than merely a workplace. The market serves as a platform for information exchange, social support, collective action, and civic participation. Historically, women vendors have played important roles in community mobilization and social movements in Manipur. This demonstrates that markets can contribute not only to economic development but also to social cohesion and democratic participation. The market demonstrates that development is not driven solely by financial investments. Strong social institutions are equally important for creating resilient communities and sustainable livelihoods.

The Challenges Behind the Success Story

Despite its remarkable achievements, the women vendors of Ima Keithel continue to face several socio-economic challenges that affect the sustainability and growth of their enterprises. One of the most significant constraints is the limited access to institutional credit, which restricts opportunities for business expansion and investment. As a result, many vendors depend on informal sources of finance, including private lenders and traditional savings systems, making them vulnerable to indebtedness and financial insecurity. The relatively low profit margins earned by many traders further limit their ability to save, accumulate assets, and reinvest in their businesses. In addition, infrastructure constraints, such as inadequate storage facilities, congestion, sanitation issues, and transportation difficulties, reduce the efficiency of market operations. The increasing presence of alternative retail outlets and changing consumer preferences have intensified market competition, creating uncertainty in income and livelihoods. Women vendors also shoulder substantial family responsibilities, balancing business activities with household chores, childcare, and caregiving duties, which significantly increase their workload.

Ima Keithel: A Market That Became a Solution

Perhaps the most remarkable feature of Ima Keithel is its ability to transform many of the challenges traditionally faced by women into opportunities for empowerment and economic advancement. In a context where limited employment opportunities often restrict women's participation in the workforce, the market provides self-employment and entrepreneurship opportunities for thousands of women. Ima Keithel further addresses financial exclusion through traditional institutions such as *Marup*, which provide savings and credit support when formal financial services are inaccessible. Beyond economic benefits, the market combats social isolation by fostering strong social networks, mutual support systems, and community solidarity among women traders. It also plays a crucial role in preserving and promoting indigenous knowledge, traditional crafts, local foods, and cultural practices, thereby addressing cultural marginalization while creating livelihood opportunities. Participation in the market enhances women's self-confidence, leadership abilities, and decision-making power, both within households and in the broader community.

The Way Forward: Strengthening Women's Markets

While the resilience and entrepreneurial spirit of the women vendors of Ima Keithel are remarkable, sustained progress requires supportive policies and institutional interventions. One of the most pressing needs is improved access to affordable institutional credit through women-focused loan schemes and low-interest financing programmes that can help vendors expand their businesses and reduce dependence on informal sources of borrowing. Strengthening financial inclusion through greater banking outreach, simplified procedures, and tailored financial products would further reduce reliance on private lenders and enhance economic security. Efforts to improve financial literacy and encourage savings habits can help women build stronger financial foundations and increase their ability to invest in business growth. Equally important is investment in market infrastructure, including better storage facilities, sanitation services, transportation connectivity, and modern market amenities, which would improve operational efficiency and reduce post-harvest losses.

Lessons for the Rest of India

The experience of Ima Keithel offers several important lessons for the rest of India in designing inclusive and sustainable development strategies. First, the market demonstrates the effectiveness of women-led development, highlighting the need to promote women's leadership in economic institutions, cooperatives, self-help groups, and producer organizations. Ima Keithel further illustrates the benefits of market-led development, where strong producer-consumer linkages create opportunities for local producers while ensuring the availability of goods for urban consumers. The market's ability to preserve traditional products and cultural practices while generating economic value also highlights the importance of integrating cultural preservation with economic growth. Additionally, the challenges faced by women vendors emphasize the need for greater financial inclusion, particularly through affordable credit, accessible banking services, and women-focused financial programmes. Above all, the Mothers' Market demonstrates that truly inclusive development is achieved when women are empowered not merely as beneficiaries of welfare programmes but as entrepreneurs, leaders, decision-makers, and agents of change.

Conclusion

The significance of Ima Keithel lies not merely in the fact that it is the world's largest women-run market. Its true importance lies in the development lessons it offers. Long before concepts such as women-led development, social entrepreneurship, financial inclusion, and sustainable livelihoods became policy priorities, the women of Manipur had already built an institution embodying these principles. The Mothers' Market is both a celebration of women's achievements and a reminder of the challenges they continue to face. Yet its greatest contribution is that it transformed a marketplace into a mechanism of empowerment. Through trade, women overcame economic dependence, built social capital, preserved cultural identity, strengthened household welfare, and enhanced their role within society. For the rest of India, the lesson is clear In the heart of Imphal stands not merely a market, but a living model of inclusive development-one that the rest of India can learn from and adapt for generations to come.

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Gametology and Factors Affecting Gamete Quality in Fish

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Abstract

Gamete quality is an important factor affecting reproductive success in fish, as it directly affects the success of fertilization, embryonic development, and larval survival. The review is concerned with gametology, the science of gametes, as it applies to teleost species of interest to aquaculture. This article discusses the structural organization of fish spermatozoa and eggs and the standardized quality assessment parameters including sperm motility, concentration, and seminal plasma biochemistry assessed using Computer-Assisted Sperm Analysis (CASA). A critical assessment of criteria for egg quality including fertilization rate, hatching rate, embryonic normality and larval survival. Summary of multifactorial effects on gamete quality including broodstock nutrition, environmental stressors, broodstock age and husbandry practices. These factors are emphasized as being important for inclusion in evidence-based broodstock management protocols to optimize reproductive output in aquaculture.

Keywords: Gametology, Fish spermatozoa, Egg quality, Sperm motility, CASA, Gamete evaluation

1. Introduction

The global aquaculture industry has expanded rapidly over the past few decades and now provides more than half of all fish eaten by humans. Despite advances in species domestication and genetic improvement, a persistent bottleneck limiting productivity is the poor quality of gametes produced by captive broodstock (Migaud et al., 2013). Gametology, the complete study of gametes and their role in sexual reproduction and the continuity of heredity, has an important interdisciplinary role at the intersection of reproductive physiology, cellular biology and genetics. In finfish aquaculture this field includes production, maintenance and activation of reproductive cells during fertilization, with the entire downstream productivity of a breeding program depending on gamete quality at the moment of union (Cabrita et al., 2009).

Fish spermatozoa differ greatly from their mammalian counterparts, with teleost spermatozoa lacking an acrosomal cap and depending on micropyle-mediated egg penetration (Jamieson, 1991). In the reproductive tract, sperm are immotile and are activated only on contact with the external aquatic environment where motility lasts only seconds to minutes depending upon the species (Rurangwa et al., 2004). Fish egg quality, defined as the ability of a matured oocyte to be fertilized and develop normally (Bobe & Labbé, 2010), is influenced by broodstock age, nutritional condition, environmental conditions during oogenesis and timing of gamete collection (Kjørsvik et al., 1990). Broodstock nutrition, especially the provision of essential fatty acids, fat soluble vitamins and carotenoids (Izquierdo et al., 2001) directly affects the biochemical composition and functional competence of both sperm and eggs. Environmental factors, such as temperature, photoperiod, dissolved oxygen, and exposure to pollutants also influence gametogenesis and gamete quality.

2. Structure and Quality of Fish Sperm

2.1 Structural Organization

The fish spermatozoon is made up of three functionally distinct regions: the head, the midpiece and the flagellum. Teleost fish, unlike most other vertebrates, do not possess an acrosomal cap on the head of the sperm. This is directly related to the mechanism of egg penetration based on the micropyle, which is characteristic of fish reproduction (Jamieson, 1991). In most species, the flagellar axoneme has a canonical 9+2 arrangement of microtubule doublets, but some orders, such as the Anguilliformes and Elopiformes, tend towards a 9+0 configuration. In viviparous species, the larger sizes of the head and midpiece are a marker of evolutionary adaptation to the environments of internal fertilization.

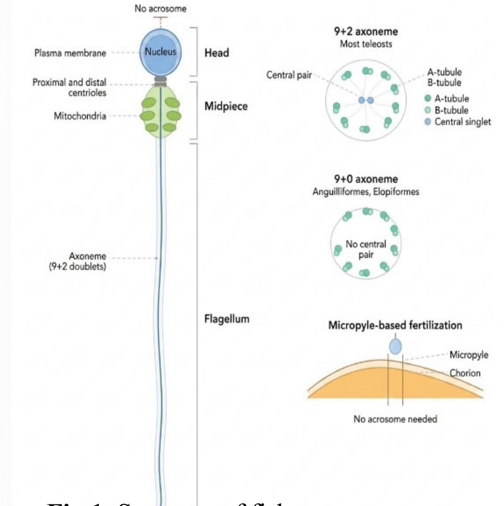

Fig 1. Structure of fish spermatozoan

2.2 Quality of Sperm

The reproductive viability of fish spermatozoa is defined as a standardized set of parameters, as defined in comparative fish reproductive biology (Rurangwa et al., 2004).

- **Motility (MOT):** The percentage of actively swimming spermatozoa. This is generally regarded as the best single predictor of fertilisation potential, with high quality samples generally above 80%.
- **Sperm Volume & Total Production (TSV/TSP):** Total seminal fluid volume and total sperm count per ejaculation, representing the overall reproductive capacity.

- **Concentration (SC):** Spermatozoa density per ml of seminal plasma calculated by hemocytometry or spectrophotometry.
- **pH & Osmolality:** The exact time of motility onset and its length are dictated by the acid and osmotic pressure of seminal plasma; deviations from species-specific optima inhibit or prematurely induce flagellar activity.
- **Total Protein Content (TPC):** The total protein concentration in seminal plasma is indicative of the biochemical environment that supports the spermatozoa.

These parameters are quantified by Computer-Assisted Sperm Analysis (CASA) and by live/dead fluorescent staining. CASA systems allow for objective measurement of kinetics including curvilinear velocity and progressive motility with high reproducibility between repeated measurements (Rurangwa et al., 2004). Standardisation of activation timing is also critical, as fish sperm motility decreases rapidly within seconds of activation; it is recommended that analysis is initiated within 6–8 seconds following activation.

2.3 Factors That Affect Sperm Quality

- **Diet:** Antioxidants such as vitamins C and E, and carotenoids in the diet contribute to protecting spermatogenic cells against oxidative damage while polyunsaturated fatty acids (DHA and ARA) help in maintaining the fluidity of the flagellar membrane and improving the fertilization ability (Izquierdo et al., 2001).
- **Environmental Conditions:** Seasonal variations in water temperature, photoperiodic variations, salinity variations and chemical pollutant exposure all synergistically act to alter seminal biochemistry and induce spermatozoal morphological abnormalities resulting in reduced fertilization potential.
- **Male Age:** Reproductive senescence gradually reduces the volume of sperm output and the quality of motility, but age-related effects in fish are less systematically documented than in females.
- **Activation Medium:** The ionic composition, pH, and osmolality of the medium used to initiate sperm motility determine the accuracy of kinetic measurements; species-specific formulations are essential for valid comparative assessments.
- **Duration of Measurement:** Temporal control of motility recording is critical. Longer observation windows yield progressively lower motility values. High speed camera capture of 0.5–2 s windows is optimal.

3. Classification, Structure and Quality of Fish Eggs (Ova)

3.1 Classification

The eggs of fish are generally divided into two groups, pelagic and demersal, according to their buoyancy in water. Pelagic eggs typical for marine broadcast spawners are positively buoyant, due to oil droplets associated with the yolk, high hydration and gelatinous surface coatings. Demersal eggs are common in freshwater taxa and are negatively buoyant, so that they settle on the substrate or adhere to benthic surfaces (Kjørsvik et al., 1990). The second axis of classification is between adhesive and non-adhesive eggs. Adhesive eggs contain surface glycoproteins that allow them to attach to substrates, while non-adhesive eggs are passively dispersed by water currents.

3.2 Structural Design

The chorion, an acellular, rigid coat of proteins and polysaccharides, forms the outermost structural layer of the fish egg and is synthesized in its entirety by the oocyte in teleosts. Below this is the vitelline membrane, encompassing the ooplasm and yolk mass. The main metabolic fuel for embryonic development prior to the beginning of exogenous feeding are yolk reserves, the abundance of which varies widely across species (Bobe & Labbé, 2010). Crucially, egg size and yolk content are independently regulated variables, each contributing to developmental success independently.

3.3 Evaluation of Egg Quality

Egg quality is the capacity of a fully matured oocyte to be fertilized and develop to normal morphology by embryogenesis (Bobe & Labbé, 2010). Poor egg quality clinically manifests as fertilization failure, developmental arrest, high embryonic mortality or teratogenic deformity. During the evaluation some parameters are considered:

- **Fertilization Rate:** An early indicator of viability, but high fertilization rates alone do not reliably predict normal embryonic progression in all species.
- **Hatching Rate:** The percentage of fertilized eggs that result in morphologically intact, viable larvae; a robust integrative measure of overall embryo quality.
- **Embryonic Normality:** Microscopic staging throughout the incubation period systematically assessing for developmental abnormalities, deformities or stage specific arrest.
- **Buoyancy & Larval Survival:** Buoyancy after hatching and early larval survival are integrative proxies of egg compositional quality which include lipid profile, carotenoid status, and hormonal conditioning.

3.4 Factors Influencing Egg Quality

- **Age of Broodstock:** Females in their prime reproductive age invariably yield eggs of greater fertilizability and developmental reliability; egg quality is significantly lower in both immature and senescent broodstock.
- **Nutritional Status:** The dietary composition of the broodstock directly controls the biochemical composition of oocytes and deficiency in essential fatty acids, fat-soluble vitamins or trace minerals may impair the structure of yolk lipid and reduce the success of development (Izquierdo et al., 2001).
- **Water Quality:** Physiological stress from sub-optimal temperature, decreased dissolved oxygen or increased ammonia levels during oogenesis impairs follicular development and integrity of egg composition.
- **Broodstock Management:** Disciplined conditioning protocols, correct sex-ratio maintenance, regular health evaluation and stress reduction are the basis of consistent high-quality egg production (Migaud et al., 2013).
- **Fertilization Technique:** Accuracy of sperm-to-egg ratio calibration, correct timing of gamete mixing and the use of species-appropriate activation media are procedural determinants of fertilization efficiency and subsequent embryo viability.

4. Conclusion

Gametology plays a pivotal role in improving reproductive efficiency and sustainable aquaculture production by ensuring high-quality sperm and eggs. Gamete quality is influenced by multiple factors, including broodstock nutrition, age, environmental conditions, water quality, and husbandry practices. Accurate evaluation using standardized techniques such as Computer-Assisted Sperm Analysis (CASA) and comprehensive egg quality assessment enables better broodstock selection and reproductive management. Integrating scientific knowledge of gamete biology with optimized breeding protocols can significantly enhance fertilization success, embryo development, and larval survival. Continued research on gamete physiology and quality assessment will further strengthen hatchery performance, genetic improvement, and long-term sustainability of the aquaculture industry.

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Germ Cell Transplantation in Fisheries: A Promising Step Toward Conservation

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Abstract

Surrogate broodstock technology based on germ cell transplantation provides a powerful approach for conservation of aquatic genetic resources and enhancement of aquaculture production at scale. In fish, germline stem cells or primordial germ cells from donor gonads or embryos can be cryopreserved, transplanted into sterilized or germ cell-depleted recipients and then reconstituted as functional gametes of donor origin under controlled conditions. The strategy avoids technical limitations of oocyte cryopreservation, maternal inheritance of mitochondria, and long generation intervals for large-bodied or late-maturing species. Successful intra- and interspecific applications have been reported in commercially valuable taxa like pufferfish and sturgeons and also in Indian major carps where cryopreserved spermatogonia are revived in allogeneic hosts. The integration of surrogate broodstock systems with genome editing and environmentally benign sterilisation tools such as thermal manipulation further creates opportunities for secure cryopreservation, rapid propagation of elite germplasm and safe restoration of endangered populations over coming decades.

Keywords: Germ cell transplantation, Surrogate broodstock, Cryopreservation, Indian major carps, Conservation aquaculture

Introduction

Conservation of genetic resources in fishes has largely focused on sperm cryopreservation. However, fish oocytes, which contain substantial yolk reserves essential for embryogenesis, are difficult to cryopreserve due to their large size and high yolk content. Revival of species using sperm alone is intrinsically incomplete because mitochondrial DNA is transmitted maternally via the oocyte. In contrast, surrogate propagation can regenerate entire species from cryopreserved gonadal tissue or germ cells, restoring both nuclear and mitochondrial genomes, and offering a powerful strategy for safeguarding endangered and commercially important fishes. The manipulation of germline stem cells (GSCs) in fish is a relatively new reproductive biotechnology that takes advantage of the developmental potential of gonadal GSCs to generate donor-derived gametes. Donor GSCs isolated from the gonads and transplanted into recipient larvae home and establish in the genital ridge, then transdifferentiate according to the host gonadal environment: donor spermatogonia in female hosts are able to generate functional oocytes, while donor oogonia in male hosts can generate spermatozoa. Surrogate hosts thus produce gametes made up entirely of donor genetics (Goto and Saito, 2019). Cryopreservation can be combined with surrogacy as male (Franěk et al., 2019a) and female (Franěk et al., 2019b) GSCs can be frozen efficiently and re-established in sterilised recipients (Lee et al., 2013; Yoshizaki and Lee, 2018; Marinović et al., 2019). Recent studies have also shown that GSC-based methods can produce genome-edited donor gametes without inducing lethality or reduced fitness in edited adults (Zhang et al., 2020; Zhang et al., 2021), thus establishing surrogate broodstock technology as a flexible platform for conservation and genetic enhancement in aquaculture.

Methods of Germ Cell Transplantation

Several germ cell transplantation strategies have been developed and tested to generate germline chimeras in fish. In general, these approaches can be divided into those based on experimental embryology and those based on reproductive biology.

Approaches Based on Experimental Embryology

These techniques involve manipulation of the early stages of the embryo before full differentiation and migration of the germ cells.

- **Blastomere transplantation (BT):** At blastula stage blastomeres are aspirated from a donor embryo and injected into a host embryo at the same stage. At this stage the germplasm distribution is not completely outlined or separated yet. The transplanted population of cells usually comprises a mixture of primordial germ cells (PGCs) and somatic blastomeres. Historically, BT resulted in relatively low efficiencies of donor-derived offspring production (approximately 11–31%). More recent refinements using PGC-enriched donor embryos and sterile recipient hosts, however, have greatly improved the efficiency of producing donor-derived progeny.
- **Blastoderm transplantation (BdT):** BdT is a more refined form of blastomere transplantation. Researchers can take a piece of the lower part of the donor blastoderm enriched for PGCs and transplant it directly into a host blastula. Localization of the marginal region of the blastodisc containing PGCs, often identified using vasa

transcripts, this method has proven to be highly efficient and has been successful in achieving mono-sex and donor-only gamete production in conjunction with sterile hybrid recipients.

Approaches Based on Reproductive Biology

Reproductive biology–driven methods, on the other hand, depend on the transplantation of specific germ cell populations such as PGCs, spermatogonia (testicular germ cells), or oogonia (ovarian germ cells) into recipients at subsequent developmental stages (larval or adult) rather than on embryology-based techniques. These methods typically follow a sequence of steps:

- **Cell isolation and visualization:** Germ cells are isolated from donor gonads or embryos. Molecular and imaging tools, including visualization of vasa expression and fluorescent labeling (e.g., green fluorescent protein [GFP]), are employed to identify, track, and enrich pure germ cell populations while minimizing contamination with somatic tissue.
- **Microinjection into post-embryonic hosts:** The isolated germ cells are microinjected into the peritoneal cavity of hatched larvae or directly into the gonads of juvenile or adult fishes instead of blastula-stage embryos.
- **Migration and incorporation:** After transplantation, donor germ cells display a characteristic homing behavior, migrating toward the recipient's genital ridge or developing gonads, colonizing these tissues, and integrating into the recipient germline.
- **Surrogate gametogenesis:** The surrogate host provides the proper microenvironment to support the maturation of the donor germ cells. The host ends up producing functional gametes (eggs or sperm) of only the donor genotype.

The second class of methodologies is especially useful for aquaculture and conservation programs as it allows the use of cryopreserved germ cells from mature or endangered species and their reconstitution in another more manageable surrogate species.

Case Studies of Germ Stem Cell Technology

Global Applications

Commercially Important Species: Tiger puffer (*Takifugu rubripes*)

Seed production of the high-value tiger puffer (*Takifugu rubripes*) has been achieved using the grass puffer (*Takifugu niphobles*) as a surrogate host. Grass puffers are smaller, easier to handle, and more practical to rear under commercial or laboratory conditions. This surrogate system enables efficient, large-scale seed production of a premium aquaculture species using a more tractable host (Hamasaki et al., 2017).

Endangered Species: Large sturgeons

Surrogate parent technologies have been applied in the Czech Republic to regenerate large critically endangered sturgeon species. Germ cells isolated from these large sturgeons were transplanted into the much smaller sturgeon species sterlet (*Acipenser ruthenus*. Large sturgeons take a long time to reach sexual maturity and need large rearing facilities. Thus, using sterlet as a surrogate host circumvents the spatial limitation and accelerates conservation efforts to maintain the genetic diversity of these threatened taxa) (Pšenička *et al*., 2015).

Indian Scenario

Germ cell transplantation (GCT) has been tried on economically important indigenous fish species in India, with a few notable case studies and ongoing research programmes. Indian researchers and their international collaborators have concentrated on Indian major carps (IMCs) - Rohu (*Labeo rohita*), Catla (*Catla catla*) and Mrigal (*Cirrhinus mrigala*), which constitute the basis of aquaculture in South Asia. Due to their large size, long maturation periods and the fact that their eggs cannot be cryopreserved due to their size and yolk content, GCT is being promoted as a revolutionary tool for cryo-banking and surrogate seed production in carp aquaculture.

Rohu-to-Catla Allogeneic Transplantation

In an important study, spermatogonial germ cells were isolated from Rohu (*Labeo rohita*), an important commercial species, and cryopreserved with cryoprotectants such as dimethyl sulfoxide (DMSO). These germ cells were thawed and tested for viability before transplantation into larvae of allogeneic host species, Catla (*Catla catla*) (Patra et al., 2016). The transplanted cells migrated to recipient Catla gonads and successfully colonized and proliferated. The present work has demonstrated that germ cells from elite or selectively bred IMC strains can be cryopreserved in liquid nitrogen and recovered in surrogate carp hosts providing an effective insurance policy for valuable commercial breeding lines.

Recipient Preparation via Thermal Manipulation in Rohu

To generate gametes derived only from the donor, the endogenous germ cells of the surrogate host must be depleted or functionally inactivated. In many studies worldwide, sterility is induced by cytotoxic agents (e.g., Busulfan) or genetic modification. On the other hand, Indian scientists have explored the possibilities of germ cell depletion in Rohu through thermal regimes. They used fluorescent membrane dyes (PKH 26 and PKH 67) to study depletion dynamics and spatial distribution of endogenous germ cells by sequentially raising water temperature up to 36 °C (Majhi and Borah, 2024). This work lays a foundation for the development of environment friendly, chemically free "blank slate" surrogate hosts from the Indian carps through controlled thermal manipulations, thereby improving the biosafety and sustainability of the surrogate-based seed production systems for commercial realization.

Conclusion

Germ cell transplantation and surrogate broodstock technology overcome limitations of oocyte cryopreservation and long generation intervals, enabling cryobanking, efficient seed production, and conservation of endangered and high-value fishes across global and Indian case studies, while eco-friendly sterilization advances support safe, sustainable commercial aquaculture systems worldwide for future genetic resource management.

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