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Smart aquaculture, higher profits: Technological innovations for a sustainable blue future

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Abstract

Aquaculture is increasingly recognized as a critical contributor to global food security, nutrition and livelihood generation. However, rising production costs, feed wastage, disease outbreaks, water scarcity and climate variability pose significant challenges to its long-term sustainability and profitability. Technological advancements offer promising opportunities to enhance aquaculture productivity while optimizing resource utilization and minimizing environmental impacts. This article highlights emerging technological interventions for developing efficient, economically viable and sustainable aquaculture systems. Key approaches include precision aquaculture through real-time water-quality monitoring, automated and intelligent feeding systems, biofloc technology, recirculating aquaculture systems (RAS), and integrated aquaponics. It further explores the applications of artificial intelligence (AI), the Internet of Things (IoT), digital farm management, improved genetics, advanced hatchery technologies and molecular disease diagnostics in strengthening farm operations and fish health management. Climate-smart aquaculture practices, efficient cold-chain management, value addition and digital market connectivity are also discussed as essential components of sustainable sectoral development. Particular emphasis is placed on the economic feasibility and practical adoption of these technologies, especially among small- and medium-scale farmers. The article highlights that technological innovation must be supported by appropriate infrastructure, technical knowledge, institutional assistance and market access to deliver meaningful benefits. Integrating scientific innovations with farmer-oriented management practices can improve productivity, profitability and resource efficiency while reducing the environmental footprint of aquaculture.

Keywords: Aquaculture; Precision fish farming; Artificial intelligence; Internet of Things; Biofloc technology; Recirculating aquaculture systems; Sustainable aquaculture; Climate-smart aquaculture.

Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors in the world, playing a vital role in meeting the increasing demand for affordable, nutritious aquatic

food. With stagnating capture fisheries, growing population pressure and increasing concerns over food security, aquaculture is no longer simply an alternative to traditional fishing; it has become an essential component of the global food system. However, the future of aquaculture cannot depend solely on increasing production. It must focus on producing more with fewer resources, reducing operational costs, improving farm efficiency and maintaining environmental sustainability.

According to the Food and Agriculture Organization (FAO, 2026), global production of aquatic resources reached approximately 235 million tonnes in 2024, comprising both aquatic animals and algae, driven primarily by the growth of aquaculture. Notably, aquaculture alone surpassed 100 million tonnes of aquatic animal production. In the same year, global per capita availability of aquatic animal foods reached to 21.3 kg, contributing approximately 15% of the world's animal protein supply. Furthermore, aquatic products accounted for approximately 36% of global aquatic animal production traded internationally, generating an estimated USD 186 billion in revenue. This development highlights the vital role of aquaculture in global food security, nutrition, livelihoods and the sustainable growth of the blue economy.

India occupies a prominent position in this transformation. The country recorded approximately 197.75 lakh tonnes of total fish production during 2024–25, from 95.79 lakh tonnes fish production in the year 2013-14 increasing a significant 106% (Department of Fisheries, 2025). This expansion reflects the growing contribution of freshwater aquaculture, coastal aquaculture, reservoir fisheries and technological interventions. Nevertheless, increasing feed costs, disease outbreaks, fluctuating market prices, water scarcity, climate variability and inefficient farm management continue to affect farmers' profitability.

In this context, technological interventions offer considerable opportunities to transform conventional aquaculture into a more productive, resource-efficient and economically viable enterprise. The objective should be simple: higher returns with lower resource consumption and a smaller environmental footprint.

1. Precision aquaculture: Making every input count

One of the most promising developments in modern aquaculture is precision fish farming. Traditionally, farmers depend on experience and visual observations to determine feeding schedules, stocking density, water exchange and other management practices. Although traditional knowledge remains valuable, it may not always identify sudden changes in water quality or fish behaviour.

Precision aquaculture integrates sensors, automated monitoring systems, digital technologies and data analytics to improve farm management. Sensors can continuously

monitor critical water-quality parameters such as dissolved oxygen, temperature, pH, salinity and, where appropriate, ammonia. The information can be transmitted to mobile phones or computer dashboards, enabling farmers to take timely corrective measures (Føre *et al*., 2018; D'Agaro, 2025).

For example, an automated aeration system can switch on when dissolved oxygen falls below a predetermined threshold. Similarly, temperature and pH monitoring can help farmers identify unfavourable conditions before they significantly affect fish health.

The economic advantage of precision aquaculture lies in preventing avoidable losses. Early identification of oxygen depletion, inappropriate feeding and deteriorating water quality can reduce mortality, improve growth and minimize unnecessary expenditure on electricity, feed and water exchange (Lindholm-Lehto *et al*., 2023).



Real-time monitoring of dissolved oxygen, temperature and pH using pond sensors connected to a mobile phone

2. Smart feeding systems: Reducing the biggest operational expense

Feed is generally one of the largest variable costs in intensive aquaculture. Depending on the species, production system and farm management, feed may account for a substantial proportion of total operating expenditure. Therefore, improving feed utilization is directly

linked to profitability (Tacon & Metian, 2015).

Conventional feeding practices often involve broadcasting feed manually at fixed times and quantities. This can result in overfeeding, feed wastage, deterioration of water quality and increased nutrient loading in culture ponds.

Automatic feeders, demand feeders, timer-based feeding systems and acoustic feeding technologies offer practical alternatives. These systems help distribute feed at predetermined intervals or in response to fish feeding activity. Advanced systems equipped with underwater cameras and artificial intelligence can assess feeding behavior and adjust feed delivery accordingly (Thornburg *et al*., 2025).

An important indicator of feeding efficiency is the feed conversion ratio (FCR), which represents the quantity of feed required to produce one unit of fish biomass gain.

For instance, an improvement in FCR from 1.8 to 1.5 means that 300 kg less feed is required to produce one tonne of biomass gain. At a hypothetical feed price of Rs. 50 per kg, this represents a saving of Rs. 15,000 per tonne of biomass gain, assuming other production conditions remain unchanged.



Automated feeding of fish using sensor-based feeders to optimize feed delivery, improve feed conversion efficiency and minimize feed wastage

3. Biofloc technology: Converting waste into a resource

Biofloc technology (BFT) is an innovative aquaculture production system that promotes the development of beneficial microbial communities within culture water. By maintaining an appropriate carbon-to-nitrogen balance and sufficient aeration, heterotrophic microorganisms assimilate nitrogenous wastes and convert them into microbial biomass (Avnimelech, 2007).

These microbial aggregates, commonly called bioflocs, can serve as an additional natural food source for cultured organisms, particularly species capable of utilizing suspended microbial particles.

Biofloc systems are especially relevant for species such as tilapia and shrimp, although their suitability depends on species-specific feeding behaviour, culture conditions and system management.

The major advantages include reduced water exchange, improved nutrient recycling and additional microbial nutrition. However, the technology requires continuous aeration, regular monitoring of dissolved oxygen, alkalinity, pH, suspended solids and carbon inputs (Matishov *et al*., 2025).

From an economic perspective, biofloc should not be considered an automatically profitable technology. Electricity consumption, carbon-source requirements, infrastructure costs and technical expertise must be carefully evaluated before investment. Its success depends on maintaining an appropriate balance between production intensity and operational expenditure.



Aerated culture tank containing suspended microbial aggregates that support nutrient recycling

4. Recirculating aquaculture systems: Producing fish with less water

Recirculating aquaculture systems (RAS) represent an advanced approach to intensive

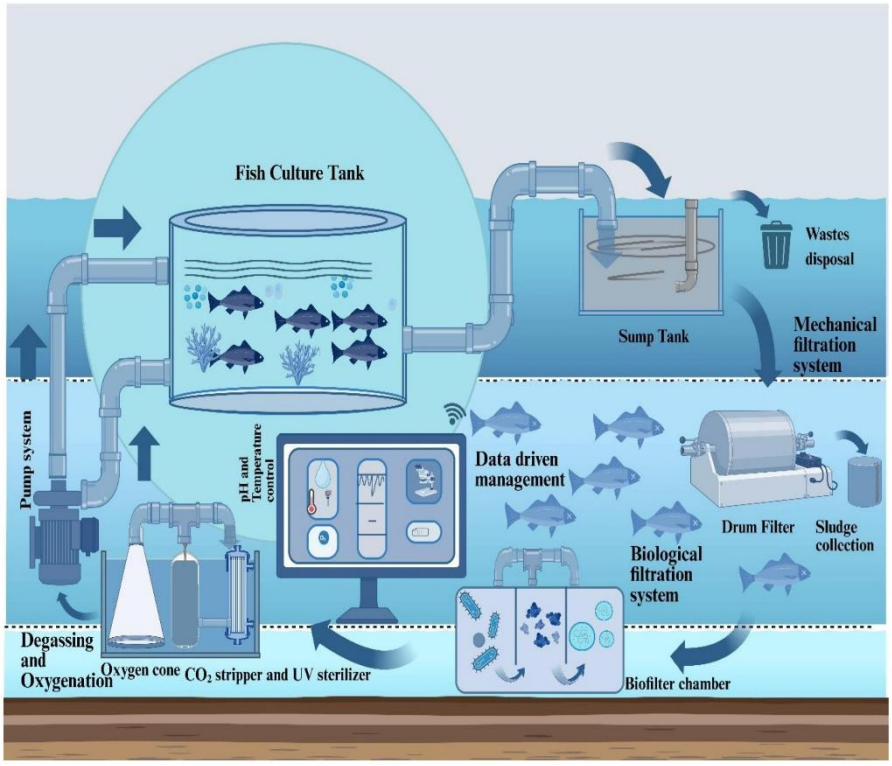
fish production in which culture water is continuously treated and reused. These systems generally include mechanical filtration, biological filtration, aeration or oxygenation, water circulation and disinfection units (Lindholm-Lehto *et al*., 2015).

Mechanical filters remove suspended solids, while biological filters facilitate the conversion of toxic ammonia into less harmful nitrogenous compounds through microbial processes. Additional treatment components may be incorporated according to production requirements.

RAS offers several advantages, including reduced water consumption, better control over culture conditions, biosecurity and the possibility of establishing fish farms closer to urban markets (Gupta *et al*., 2024).

Species such as tilapia, pangasius, seabass and selected high-value freshwater or marine fishes can be considered for RAS, depending on their biological requirements and market potential.

However, high initial investment, electricity consumption, skilled labour requirements and dependence on backup systems are important limitations. A power failure or breakdown in oxygen supply can result in rapid stock losses. Therefore, RAS is particularly suitable where water is scarce, land is limited, market access is favourable and the farm can maintain reliable technical support.



Integrated fish tanks, mechanical filtration, biological filtration, oxygenation and water recirculation

5. Aquaponics: Integrating fish and plant production

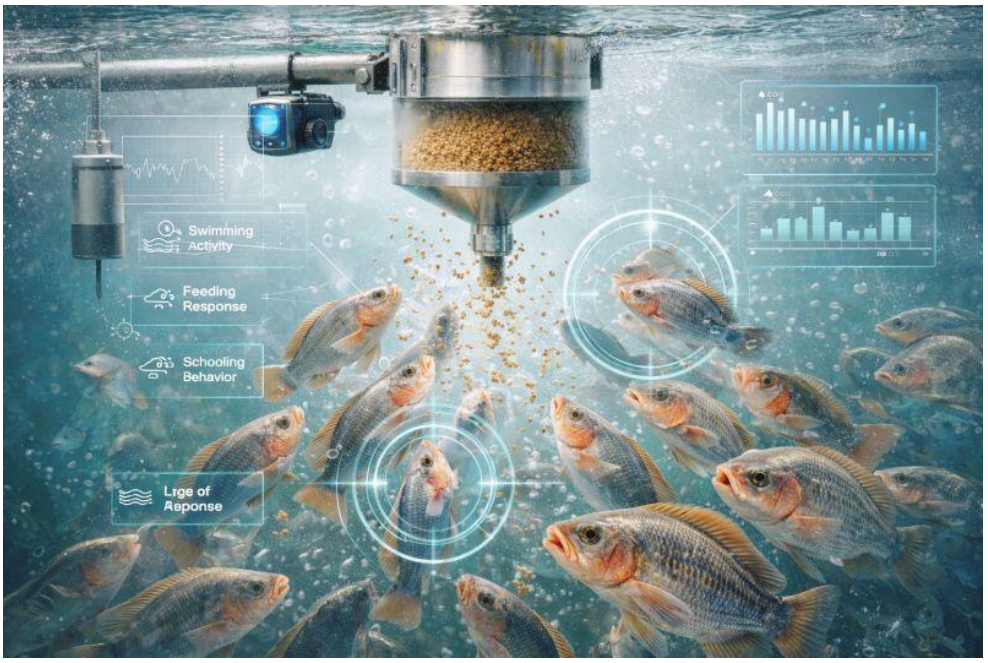
Aquaponics combines aquaculture with hydroponics, creating an integrated production system in which fish and plants are cultivated together. Nutrient-rich water from fish culture is circulated through plant-growing units, where plants utilize dissolved nutrients. The treated water is subsequently returned to the fish-rearing system (Kiggundu *et al*., 2025).

This approach creates opportunities for producing two marketable commodities within a common production framework. Leafy vegetables, herbs and certain fruiting crops can be cultivated alongside suitable fish species such as tilapia.

Aquaponics can improve nutrient-use efficiency and reduce the discharge of nutrient-rich effluents. It also offers opportunities for urban agriculture, educational institutions, small-scale entrepreneurs and peri-urban farming (Okomoda *et al*., 2023).

Nevertheless, profitable aquaponics requires careful selection of fish and plant species, balancing nutrient requirements, maintaining suitable water quality and identifying reliable markets for both products. The additional investment in plumbing, pumps, filtration and plant-growing structures must be justified through market returns.





Fish culture integrated with hydroponic vegetable production through a shared water circulation system

6. Artificial intelligence, IoT and digital farm management

The integration of artificial intelligence (AI), the Internet of Things (IoT), remote sensing and mobile applications is opening new possibilities in aquaculture management.

IoT-enabled sensors can collect real-time information from ponds, tanks and cages. Cloud-based platforms can store and analyze these data, while mobile applications can provide farmers with alerts and management recommendations.

Artificial intelligence can support several farm operations, including monitoring fish activity and feeding behaviour through underwater cameras; estimating fish biomass and growth; detecting abnormal swimming behaviour that may indicate stress or disease; optimizing feeding schedules; predicting changes in water quality using historical and real-time data; and supporting harvest planning and farm-level production decisions (Chatterjee & Sanyal, 2026).

Recent developments in AI-enabled aquaculture demonstrate the potential of combining sensor networks, predictive analytics and automated decision-making to improve farm efficiency and resource management (Huang & Khabusi, 2025).

For small-scale farmers, affordable mobile-based advisory services may be more practical than expensive automated systems. Digital platforms can also help farmers access weather forecasts, market information, technical guidance and government support schemes.

The National Fisheries Digital Platform introduced under the Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana is an important step towards improving digital integration in India's fisheries and aquaculture sector.

Automated feeder and underwater camera used to monitor feeding behaviour and reduce feed wastage

7. Climate-smart aquaculture: Preparing farms for environmental uncertainties

Climate change is emerging as a major challenge to aquaculture through increasing water temperatures, irregular rainfall, floods, droughts, salinity fluctuations and extreme weather events. These changes can influence fish growth, feeding efficiency, dissolved oxygen availability, disease occurrence and overall farm productivity (Barange *et al*., 2018).

Climate-smart aquaculture involves selecting suitable species and strains, adopting water-efficient production systems, improving farm infrastructure and strengthening early-warning mechanisms.

Practical interventions include cultivating species and strains suited to local temperature and water conditions; maintaining appropriate pond depth and water reserves; using aeration and oxygen monitoring to manage heat-related oxygen depletion; developing integrated farming systems to diversify farm income; improving pond embankments and drainage facilities to withstand floods; and using weather information and early-warning systems to plan stocking, feeding and harvesting.

Integrated aquaculture systems, including fish-cum-duck farming, fish-cum-paddy farming and aquaculture integrated with horticulture can also diversify production and improve resource utilization when appropriately designed (Maulu *et al*., 2021).

8. Improved genetics, hatchery technology and disease management

The profitability of aquaculture begins long before fish are stocked in grow-out ponds. The quality of seed and broodstock has a direct influence on survival, growth, uniformity and final harvest.

Improved hatchery management, quality broodstock development, selective breeding and molecular tools can contribute to the production of healthy and fast-growing seed. Genetic improvement programmes can help develop strains with desirable characteristics such as faster growth, improved feed efficiency, disease tolerance and adaptation to local environmental conditions (Robinson *et al*., 2023).

At the same time, molecular diagnostics, rapid disease detection kits, biosecurity protocols and responsible health management can reduce the risk of disease-related production losses.

Regular screening of seed, disinfection of equipment, proper quarantine procedures and maintaining appropriate stocking densities are essential components of preventive health

management. Technology should complement, rather than replace, good husbandry practices. The use of antibiotics and other therapeutic agents must follow responsible veterinary and aquaculture health guidelines.

9. Value addition, cold-chain management and market connectivity

Increasing production alone does not guarantee higher profits. Farmers must also receive better prices for their produce. Post-harvest losses, inadequate cold storage, poor transportation and dependence on intermediaries can significantly reduce the income received by aquaculture farmers.

Technological interventions in harvesting, icing, refrigerated transportation, hygienic handling, processing and packaging can improve product quality and market value.

Digital marketing platforms, farmer-producer organizations, direct marketing arrangements and electronic marketplaces can help farmers access consumers, processors and institutional buyers.

Value-added products such as fish fillets, fish pickles, dried fish, ready-to-cook products and hygienically packed seafood can provide additional income opportunities. Traceability systems and digital farm records can further improve consumer confidence and facilitate access to quality-conscious markets (Ababouch *et al*., 2013; FAO, 2026).

10. Making technology economically viable for farmers

Although modern technologies offer considerable benefits, their adoption must be guided by economic feasibility rather than technological appeal alone. A technology that increases production but also increases electricity, feed, labour and maintenance costs may not necessarily improve profitability. Farmers should therefore assess the investment requirements and expected financial returns before adopting a new production system (Kantal *et al*., 2025).

The following indicators are useful for evaluating farm performance:

- Feed conversion ratio: Measures feed utilization efficiency.
- Survival percentage: Indicates the proportion of stocked animals surviving until harvest.
- Production cost per kilogram: Represents total production expenditure divided by harvested biomass.
- Net operating profit: Indicates the financial return after deducting operating expenses from revenue.
- Benefit-cost ratio: Compares monetary benefits with costs incurred.
- Water productivity: Measures the quantity of fish produced relative to water consumed.
- Energy productivity: Evaluates fish production relative to energy consumption.

A gradual approach to technology adoption is often appropriate for small and medium-scale farmers. Starting with affordable interventions such as water-quality test kits, aerators,

automatic feeders and digital farm records can generate practical improvements without requiring heavy capital investment.

Government-supported schemes, institutional credit, farmer training, demonstration farms and technical extension services can further accelerate the adoption of appropriate technologies.

Conclusion: The future belongs to smarter aquaculture

The future of aquaculture will depend not simply on producing more fish, but on producing fish more efficiently, responsibly and profitably. Precision aquaculture, smart feeding, biofloc technology, recirculating systems, aquaponics, artificial intelligence, improved genetics and climate-smart management offer significant opportunities to transform the sector.

However, technology must be selected according to the species cultured, farm size, water availability, electricity supply, investment capacity and market demand. Not every advanced system is suitable for every farmer.

The way forward is to bridge the gap between scientific innovation and practical farm-level application. Fisheries research institutions, universities, government departments, entrepreneurs and farmers must work together to develop affordable, locally adaptable and economically viable technologies.

The success of sustainable aquaculture should be measured not only by tonnes of fish produced, but also by the income generated for farmers, resources conserved, environmental impacts minimized and nutritious aquatic food made accessible to society.

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