International Journal of Science, Environment and Technology, Vol. 15, No 1, 2026, 78 – 92

ISSN 2278-3687 (O)
2277-663X (P)

SMART SENSORS, INTERNET OF THINGS AND ARTIFICIAL INTELLIGENCE IN INDIAN FRESHWATER AQUACULTURE: A REVIEW OF TECHNOLOGICAL INNOVATIONS AND SUSTAINABLE IMPACTS

Satyajit Belsare[1] and Krupesh Sawant[2]*

[1]Professor, Department of Aquaculture, College of Fishery Science, Nagpur, MAFSU, Nagpur, India

[2]Senior Research Assistant (*Corresponding Author*), College of Fisheries, Ratnagiri, Dist. Ratnagiri

Abstract: Indian freshwater aquaculture has emerged as a cornerstone of national food security, rural livelihood support and export earnings, contributing over 70 percent of the country's total fish production. While intensification of pond-based culture systems has substantially increased productivity, it has concurrently exacerbated vulnerabilities including dissolved oxygen depletion, ammonia toxicity, disease outbreaks and climate-induced production risks. Traditional monitoring practices relying on intermittent manual observations remain inadequate for tropical freshwater environments where water quality parameters fluctuate rapidly. The integration of smart sensors, Internet of Things platforms and Artificial Intelligence offers significant potential for real-time water quality monitoring, early warning systems and data-driven farm management. This review examines recent advancements in sensor-based water quality monitoring, wireless data transmission, and AI applications for dissolved oxygen forecasting, feeding optimization and disease prediction relevant to Indian freshwater aquaculture systems including carp polyculture, pangasius and tilapia farming. Socio-economic feasibility, infrastructural constraints and policy-supported adoption strategies are critically examined with special emphasis on smallholder inland farmers. The review highlights that successful digital transformation must prioritize affordability, operational simplicity and farmer-centric design. Indigenous innovation, region-specific predictive models and government-supported digital aquaculture initiatives under schemes such as Pradhan Mantri Matsya Sampada Yojana are essential for sustainable intensification. Precision freshwater aquaculture, when appropriately contextualized, can enhance productivity, resilience and long-term sustainability in India.

Keywords: Freshwater aquaculture; Precision aquaculture; Internet of Things; Artificial Intelligence; Indian Major Carps; Water quality monitoring; Smallholder farmers.

1. Introduction

India ranks among the world's leading producers of freshwater aquaculture, with inland systems contributing approximately 70 to 75 percent of the nation's total fish production of 16.24 million metric tons during 2021-22 [1, 2]. The freshwater aquaculture sector is dominated by Indian Major Carps including *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*, along with expanding cultivation of pangasius (*Pangasianodon hypophthalmus*) and tilapia

*Received Feb 10, 2026 * Published Feb 20, 2026 * www.ijset.net*

(*Oreochromis niloticus*). This sector supports the livelihoods of over 14 million fishers and fish farmers while ensuring nutritional security for millions of consumers [1, 2]. The growth from traditional extensive systems to semi-intensive and intensive culture practices has significantly enhanced productivity, with average carp yields increasing from about 500 kg per hectare per year in the 1970s to over 3,000 kg per hectare per year in contemporary systems.

However, this intensification has brought complex management challenges. Freshwater ponds in tropical climates experience pronounced daily and seasonal changes that affect fish health and production. Dissolved oxygen often drops to critical levels below 3 mg per liter during early morning hours due to respiration of fish, plankton and bottom-dwelling organisms. High feeding rates in intensive systems lead to accumulation of uneaten feed and waste, resulting in elevated ammonia levels. Sudden die-off of algal blooms, often triggered by weather changes, can rapidly destabilize pond conditions, causing oxygen depletion and fish mortality. Under such dynamic conditions, traditional monitoring based on periodic manual observations, typically once or twice daily, fails to detect rapid deterioration, leaving farmers vulnerable to undetected stress and losses.

Precision aquaculture integrates digital monitoring and predictive analytics to enable real-time management [3, 4]. Globally, sensor networks and AI-based models are transforming aquaculture practices through continuous surveillance, early warning systems and automated control [5, 6]. However, transferring these technologies to Indian conditions requires careful adaptation to local socio-economic conditions, infrastructure limitations and the specific characteristics of tropical carp-based polyculture systems.

This review aims to synthesize current technological developments in sensor-based monitoring and AI applications relevant to freshwater aquaculture, examine their applicability for Indian production systems, analyze adoption constraints, and propose pathways for sustainable technological integration benefiting smallholder farmers.

2. WHY FRESHWATER AQUACULTURE NEEDS SMART TECHNOLOGIES

Water Quality Challenges in Tropical Pond Systems

Freshwater aquaculture ponds in India are dynamic ecosystems where water quality parameters fluctuate considerably. Dissolved oxygen follows a predictable daily cycle, reaching peak levels in late afternoon due to photosynthetic activity and declining to minimum levels just before dawn. In intensively stocked carp ponds with high feeding rates, pre-dawn oxygen depletion is a common cause of fish mortality. Unlike temperate regions where oxygen problems may be seasonal, tropical ponds experience oxygen stress throughout the year, particularly during cloudy weather when photosynthesis is reduced.

Ammonia accumulation presents another significant challenge. Carp and pangasius excrete ammonia directly into water, and bacterial decomposition of organic matter adds to the nitrogen load. At pH above 7.5 and temperatures above 25°C, a substantial portion of ammonia exists in the toxic unionized form. Sub-lethal ammonia exposure reduces growth, suppresses immune function and increases disease susceptibility. Traditional monitoring with chemical test kits provides only occasional snapshots, missing dangerous spikes that may occur after heavy feeding or during algal die-offs.

Temperature fluctuations in shallow ponds can exceed 5 to 6°C within a single day, affecting metabolic rates, oxygen solubility and the toxicity of ammonia. Sudden temperature drops during monsoon rains can cause thermal stress and trigger disease outbreaks.

Limitations of Traditional Monitoring Practices

Most Indian fish farmers rely on visual observation of fish behavior and occasional water testing using chemical kits. Fish showing surface respiration or reduced feeding indicate problems, but by then stress or mortality has already occurred. Testing once daily for dissolved oxygen, typically during morning hours, may not detect afternoon supersaturation or capture the rate of nighttime decline.

The experience of progressive farmers demonstrates that more frequent monitoring enables earlier intervention. However, manual monitoring every 2 to 3 hours throughout the night is impractical for farmers managing multiple ponds. This gap between monitoring needs and practical capability creates the rationale for automated, continuous monitoring systems.

3. SENSOR TECHNOLOGIES FOR AQUACULTURE MONITORING

Types of Sensors Used in Fish Ponds

Several types of sensors are now available for monitoring pond water quality. Dissolved oxygen sensors are the most critical for aquaculture. Two main types are used: electrochemical sensors that generate electrical signals proportional to oxygen concentration, and optical sensors that measure oxygen by fluorescence quenching. Optical sensors have become preferred because they require less frequent calibration and are less affected by fouling [7].

pH sensors continuously measure acidity or alkalinity, which affects ammonia toxicity and many biological processes. Temperature sensors are essential because nearly all biological rates and chemical equilibria depend on temperature. Ammonia sensors, though less common, are increasingly available and valuable for intensive culture systems.

Modern multiparameter probes combine several sensors in a single waterproof housing, simplifying deployment and reducing cost. These probes can be suspended in ponds at desired depths and connected to data logging equipment.

Sensor Placement and Maintenance Considerations

For accurate monitoring, sensors should be placed at depths representing the pond environment. In carp polyculture, where fish occupy different depths, monitoring at 1 to 1.5 meters depth typically provides representative values. Sensors must be protected from direct sunlight, which can cause erroneous temperature readings and accelerate fouling.

Biofouling, the growth of algae and bacteria on sensor surfaces, is a major practical challenge in productive fish ponds [7]. Optical sensors are less susceptible than electrochemical types but still require periodic cleaning. Automated cleaning systems using mechanical wipers or air jets reduce maintenance frequency but increase cost. Farmers must understand that even the best sensors require regular inspection and calibration.

4. INTERNET OF THINGS: CONNECTING PONDS TO FARMERS

What IoT Means for Aquaculture

The Internet of Things in aquaculture simply means connecting pond sensors to communication devices that transmit data to farmers' mobile phones or computers. Instead of visiting each pond to take readings, farmers can view real-time water quality information from their homes or even while away from the farm. When parameters exceed safe ranges, the system sends alerts, enabling timely intervention.

A typical IoT system for aquaculture includes sensors in the pond, a small solar-powered data logger that collects sensor readings, a communication device that transmits data using mobile networks or long-range radio, and a mobile application or web dashboard where farmers view data and receive alerts.

Communication Options for Rural Areas

Several options exist for transmitting data from ponds to farmers. Mobile networks using GSM or GPRS are widely available in India and work well where cellular coverage is reliable. Data is transmitted to cloud servers and can be accessed through internet-connected devices. This approach requires a SIM card and modest data plan for each monitoring station [8].

Where mobile coverage is poor, LoRa technology offers an alternative. LoRa stands for Long Range and uses radio waves to transmit data over distances of 5 to 15 kilometers [9]. Multiple ponds within an area can send data to a single gateway, which then connects to the internet. This approach works well for clusters of ponds and has low power requirements, allowing battery operation for months.

For farmers with multiple ponds in close proximity, mesh networks using Zigbee protocol allow sensors to relay data through each other to a central collection point [10]. This eliminates the need for each pond to have its own long-range communication device.

Powering Monitoring Systems

Continuous monitoring requires reliable power. Solar-powered systems have proven most practical for Indian conditions, combining a small solar panel, charge controller and battery [11]. Properly sized systems operate throughout the year, even during monsoon months with reduced sunlight. Battery capacity must accommodate several days of operation without sunshine.

Some systems use duty-cycling, where sensors take measurements at intervals rather than continuously. Measuring every 15 to 30 minutes provides adequate data for most purposes while substantially reducing power consumption. Critical periods like pre-dawn hours can be monitored more frequently.

5. ARTIFICIAL INTELLIGENCE: MAKING SENSE OF POND DATA

What AI Offers to Fish Farmers

Artificial Intelligence in aquaculture means using computer programs that learn from data to predict future conditions and recommend actions. Rather than following fixed rules, AI systems adapt based on experience with specific ponds and conditions. For farmers, this translates to early warnings of approaching problems and advice on when to aerate, feed or harvest.

The most valuable AI applications for Indian aquaculture include predicting oxygen crashes, optimizing feeding, and assessing disease risk. These applications address the major causes of production loss and inefficiency in carp and pangasius farming.

Predicting Dissolved Oxygen Problems

Dissolved oxygen prediction is the most developed AI application for freshwater aquaculture. By analyzing historical data from a pond, including oxygen levels, temperature, time of day, weather conditions and feeding events, AI models learn patterns that precede oxygen depletion [12]. These models can forecast oxygen levels 6 to 24 hours ahead with useful accuracy.

For a carp farmer, an alert that oxygen will drop below 3 mg per liter at 4 AM allows preventive aeration starting at midnight, preventing stress and mortality. Without prediction, the farmer might notice the problem only at dawn when fish are already gasping at the surface. Early warning also enables more efficient aeration; rather than running aerators all night from midnight to sunrise, the farmer might run them only from 2 AM to 5 AM based on predictions, saving electricity costs.

Research in carp ponds shows that AI-based aeration control can reduce energy consumption by 30 to 50 percent while improving oxygen conditions [13]. This represents significant savings, as aeration is a major operating cost in intensive aquaculture.

Optimizing Feed Management

Feed accounts for 50 to 70 percent of operating costs in carp and pangasius farming. Improving feed conversion by even 5 percent substantially affects profitability. AI systems help optimize feeding by analyzing how fish respond to feeding events under different environmental conditions [14, 15].

Feed demand varies with temperature, oxygen levels and fish size. On days when oxygen is low, fish eat less and convert feed poorly. Feeding the same amount as on good days wastes feed and pollutes the water. AI systems that integrate real-time sensor data with growth models can recommend daily feeding amounts adjusted to current conditions.

Some advanced systems use underwater cameras or acoustic sensors to detect when fish stop feeding actively, automatically stopping feed delivery. This prevents waste and reduces nutrient loading. While such systems are more complex and expensive, they demonstrate the direction of technological development.

Early Warning of Disease Risk

Disease outbreaks in aquaculture are often triggered by environmental stress. Rapid temperature changes, low oxygen, high ammonia and other stressors suppress fish immune systems, allowing opportunistic bacteria to cause disease. AI systems can integrate multiple stress indicators to assess disease risk and alert farmers to take preventive action [16].

For example, a combination of falling oxygen, rising ammonia and an approaching weather front might signal high risk of bacterial infection in the coming days. The farmer could then reduce feeding, increase aeration, or apply immunostimulants or probiotics as preventive measures. Early intervention based on risk assessment is more effective and less costly than treating disease after it appears.

Computer vision systems using cameras can also detect changes in fish behavior that precede disease outbreaks [17]. Fish that swim erratically, congregate near inlets, or reduce feeding activity may be showing early signs of stress or infection. While such systems remain expensive for small farmers, shared systems serving farmer groups may become feasible.

6. SMART TECHNOLOGIES FOR INDIAN FARMING SYSTEMS

Adapting Technologies for Carp Polyculture

Carp polyculture presents unique characteristics that influence technology requirements. Multiple species occupying different ecological niches mean that oxygen and water quality conditions affect species differently. Surface-dwelling catla may show stress earlier than bottom-dwelling mrigal. Monitoring systems must therefore track conditions throughout the water column rather than at a single depth.

Feeding in carp polyculture typically uses a combination of supplementary feed and pond fertilization. Unlike single-species cage culture where precise feeding is straightforward, optimizing feed input in polyculture requires understanding how different species utilize different food sources. AI systems for Indian conditions must therefore be trained on local data rather than relying on models developed for salmon or tilapia monoculture.

Pangasius farming, increasingly common in parts of India, involves extremely high stocking densities and feeding rates. Oxygen demand in pangasius ponds is exceptionally high, and crashes can occur rapidly. Continuous monitoring and predictive alert systems are particularly valuable for pangasius farmers, where losses from oxygen depletion can be catastrophic.

Smallholder-Friendly System Design

The majority of Indian fish farmers operate less than 2 hectares of pond area and have limited capital for technology investment. For these farmers, system design must prioritize affordability, simplicity and reliability [11].

Group adoption through farmer cooperatives or producer organizations offers one pathway. A shared monitoring system serving 10 to 20 ponds in a cluster reduces per-farmer cost while providing benefits to all participants. The cooperative employs a trained operator who maintains equipment and interprets data for members. This model has worked well for other agricultural technologies and could be adapted for aquaculture.

Service-based models where technology companies provide monitoring as a service for a monthly fee rather than selling equipment outright also improve accessibility. Farmers pay for the service from operating savings, avoiding large upfront investments. Companies retain ownership and responsibility for maintenance, addressing the technical support gap.

Government subsidy programs under schemes such as Pradhan Mantri Matsya Sampada Yojana can further reduce adoption barriers. Targeted support for small and marginal farmers, women farmers and scheduled caste and tribe beneficiaries can ensure that technology benefits reach those most in need.

7. EVIDENCE FROM LITERATURE: WHAT RESEARCH SHOWS

Research on smart aquaculture technologies has grown rapidly in recent years. Early studies established that wireless sensor networks could reliably monitor pond conditions [7]. Subsequent work demonstrated that machine learning algorithms could predict oxygen levels accurately enough for practical farm use [12]. Most recent research integrates multiple technologies and emphasizes sustainability outcomes [5, 6].

Table 1. Representative Studies on Smart Aquaculture Technologies

Sr.No	Technology Focus	Lead Author	Year	Key Findings for Farmers
1	IoT monitoring systems	Liu et al. [6]	2025	Integrated monitoring improves resource efficiency in ponds
2	AI aquaculture models	Yang et al. [5]	2024	AI enables real-time management decisions and reduces losses
3	Precision fish farming	Føre et al. [3]	2018	Framework for using technology to improve production
4	Oxygen forecasting	Zhang et al. [12]	2022	Neural networks predict oxygen 24 hours ahead accurately
5	Automated aeration	Kim et al. [13]	2022	Smart aeration reduces energy use by 30-50%
6	Precision feeding	Cashion et al. [14]	2021	AI feeding improves feed conversion and reduces cost
7	LoRa monitoring	Rahman et al. [9]	2023	Low-cost radio communication works well for pond clusters

Sr.No	Technology Focus	Lead Author	Year	Key Findings for Farmers
8	Climate modeling	Islam et al. [18]	2023	Integrating weather data improves pond management
9	Disease prediction	Rahman and Islam [16]	2022	Environmental monitoring helps forecast disease risk
10	Solar-powered IoT	Sharma et al. [11]	2022	Solar systems enable monitoring in areas with unreliable power

8. SUSTAINABILITY AND ECONOMIC BENEFITS

Environmental Benefits

Smart monitoring and AI management contribute to environmental sustainability in several ways. Precision feeding reduces feed waste, which means less nitrogen and phosphorus entering ponds and downstream waters [15]. Every kilogram of feed saved reduces environmental loading by approximately 30 to 50 grams of nitrogen and 5 to 10 grams of phosphorus.

Energy optimization through predictive aeration reduces electricity consumption and associated carbon emissions. Solar-powered monitoring further reduces the carbon footprint of aquaculture operations.

Digital record-keeping enables farmers to document their environmental performance, supporting sustainability certification and access to premium markets. Export-oriented farmers increasingly require such documentation to meet international buyer requirements [19].

Economic Benefits for Farmers

For individual farmers, economic benefits arise from multiple sources. Reduced mortality from early warning systems typically saves 5 to 15 percent of stock that might otherwise be lost to oxygen depletion or disease. Improved feed conversion saves 5 to 10 percent on feed costs. Reduced aeration electricity consumption saves 30 to 50 percent on energy costs.

Labor savings from automated monitoring free farmers for other productive activities. Instead of spending hours traveling between ponds taking measurements, farmers can view all pond data from their mobile phones and focus effort where intervention is needed.

Better information also supports marketing decisions. Farmers who can reliably predict harvest dates and quantities can negotiate better prices and coordinate with buyers more effectively.

Affordability for Small Farmers

The economics of smart aquaculture depend critically on system cost. Current commercial systems cost ₹50,000 to ₹150,000 per pond, which is prohibitive for most small farmers. However, costs are falling as technology advances and manufacturing scales up. Indigenous development of sensors and systems could further reduce costs.

Group ownership models substantially improve affordability. A system costing ₹100,000 shared by 10 farmers costs each only ₹10,000, well within reach given the potential benefits. Service models with monthly fees of ₹1,000 to ₹2,000 per farmer also make technology accessible without large capital outlay.

Government support through subsidy programs can accelerate adoption. If PMMSY or state schemes cover 50 to 75 percent of costs for small farmers, adoption could spread rapidly, driving further cost reductions through economies of scale.

9. CHALLENGES AND CONSTRAINTS IN INDIAN CONDITIONS

Technical Challenges in Pond Environments

Sensor biofouling remains a significant practical challenge in productive fish ponds [7]. Algae and bacteria grow rapidly on sensor surfaces, gradually reducing accuracy until cleaning restores function. In smallholder systems with limited technical support, biofouling can render sensors unreliable within weeks. Mechanical wipers, copper coatings and UV devices help but add cost and complexity.

Power supply reliability varies widely across rural India. While solar systems address this challenge, they require proper sizing and battery maintenance. Farmers must understand that batteries require replacement every 2 to 3 years, adding to long-term costs.

Connectivity limitations affect data transmission in remote areas. While LoRa technology helps, gateway installation requires internet backhaul and technical configuration beyond typical farmer capabilities. Service providers must handle this infrastructure.

Climate and Environmental Variability

Climate change introduces additional uncertainty. Rising temperatures increase metabolic rates and oxygen demand while reducing oxygen solubility. More erratic rainfall affects pond hydrology and water quality. Extreme events like cyclones and floods can destroy monitoring infrastructure [18].

Seasonal variability in tropical monsoon climates creates distinct production phases with different monitoring requirements. Models trained on dry season data may not perform well during monsoons. Continuous model updating with local data helps address this challenge.

Human and Institutional Factors

Limited technical familiarity among farmers can impede effective technology use, even when systems are installed [11]. User interfaces must accommodate varying literacy levels, using simple visual displays and voice alerts in local languages rather than complex graphs and numerical readouts.

Extension services currently lack capacity to support digital aquaculture. Fisheries extension personnel trained in traditional practices need training in sensor operation, data interpretation and troubleshooting. Curriculum updates at fisheries colleges and in-service training programs are needed.

Credit constraints limit farmers' ability to invest in technology. Most small farmers rely on informal credit at high interest rates. Integrating smart aquaculture equipment within agricultural credit frameworks, with appropriate subsidy support, would substantially enhance adoption.

10. FUTURE DIRECTIONS FOR RESEARCH AND DEVELOPMENT

Developing Affordable Systems for Small Farmers

Research should prioritize low-cost sensor development using indigenous manufacturing. India's electronics manufacturing capabilities have grown substantially; applying these to aquaculture sensors could reduce costs by 50 percent or more. Simplified systems measuring only the most critical parameters, dissolved oxygen and temperature, could be produced for under ₹10,000.

Mobile applications designed for farmers with limited technical background should use voice interfaces in local languages, simple color-coded alerts and pictorial guidance. Farmers should not need to understand complex graphs; the system should tell them clearly what action to take.

Building Indian Datasets for AI Models

AI models trained on temperate aquaculture data may not perform well in tropical carp ponds. Research institutions and progressive farmers should collaborate to build open datasets of pond conditions, feeding rates, oxygen dynamics and production outcomes across India's major aquaculture regions [12, 18].

These datasets would enable development of region-specific predictive models accounting for local climate patterns, species combinations and management practices. Models trained on local data will provide more accurate predictions and useful recommendations than generic alternatives.

Integrating Weather and Climate Information

Combining pond monitoring data with weather forecasts improves prediction accuracy [18]. If a weather model predicts cloud cover and reduced photosynthesis, oxygen forecasts can be adjusted accordingly. If a cold front is approaching, disease risk models can factor in temperature stress.

Government meteorological services could provide tailored forecasts for aquaculture, including solar radiation predictions useful for oxygen modeling and extreme weather warnings enabling protective measures.

Strengthening Extension and Support Systems

Training programs should prepare fisheries extension personnel to support digital aquaculture. This includes understanding sensor operation, interpreting data, troubleshooting common problems and helping farmers use information for decision-making. Demonstration farms where farmers can see technologies working in local conditions build confidence and stimulate adoption.

Farmer producer organizations should be supported to adopt group ownership models and employ trained operators who maintain shared systems and interpret data for member farmers. This addresses both cost and technical support challenges.

11. POLICY SUPPORT FOR DIGITAL AQUACULTURE

Government Schemes and Subsidies

The Pradhan Mantri Matsya Sampada Yojana provides a framework for supporting technology adoption in fisheries. Targeted subsidies for smart monitoring systems, with higher support for small and marginal farmers, women and disadvantaged groups, could accelerate adoption. Support for farmer producer organizations to invest in shared infrastructure would extend benefits to more farmers.

State governments can complement central schemes with their own initiatives. States with significant aquaculture production, including Andhra Pradesh, West Bengal, Odisha, Bihar and Maharashtra, could establish demonstration projects showcasing smart aquaculture technologies adapted to local conditions.

Infrastructure Development

Reliable internet connectivity remains essential for cloud-based monitoring. Continued expansion of mobile and broadband infrastructure under Digital India initiatives will benefit aquaculture as well as other sectors. For areas where connectivity remains challenging, LoRa-based systems with satellite backhaul for gateways could provide alternatives.

Solar-powered monitoring reduces dependence on grid electricity, but quality solar equipment and batteries must be available affordably. Quality assurance mechanisms preventing sale of substandard equipment protect farmers from poor-performing systems.

Standards and Data Governance

As digital aquaculture expands, standards for data formats and communication protocols will enable different systems to work together and share data. Open standards prevent vendor lock-in and allow farmers to mix equipment from different suppliers.

Clear policies on data ownership and privacy assure farmers that their production data will not be misused. Farmers should control who accesses their data and how it is used, with benefits shared if data contributes to research or commercial applications.

12. CONCLUSION

Smart sensors, Internet of Things platforms and Artificial Intelligence offer significant opportunities to improve Indian freshwater aquaculture through continuous monitoring, early warning of problems and optimized management. These technologies can reduce mortality from oxygen depletion, improve feed efficiency, enable early disease detection and support environmentally responsible production.

The evidence from international research demonstrates that these technologies work technically and provide economic benefits. However, successful adoption in India depends critically on adapting technology to local conditions and farmer capabilities. Systems must be affordable, simple to use and robust enough for tropical pond environments. Indigenous development, region-specific AI models trained on Indian data, and user interfaces designed for farmers with limited technical background are essential.

Institutional support through targeted subsidies, extension training, and facilitation of group adoption models can accelerate uptake while ensuring benefits reach smallholder farmers. Demonstration projects showing tangible benefits in local conditions build confidence and stimulate demand.

Climate change makes real-time monitoring and predictive management increasingly important. As weather becomes more variable and extreme events more frequent, farmers need better information to manage risks. Smart aquaculture technologies can help build resilience into production systems.

When thoughtfully adapted to Indian conditions and smallholder needs, precision aquaculture technologies can contribute substantially to sustainable intensification, climate resilience and livelihood security in India's inland aquaculture sector. The goal is not technology for its own sake, but practical tools that help farmers produce more efficiently, reduce risks and improve their livelihoods.

REFERENCES

[1] FAO. 2023. *The State of World Fisheries and Aquaculture 2023*. Food and Agriculture Organization of the United Nations, Rome, Italy.

[2] MPEDA. 2023. *Indian Aquaculture Statistics 2023*. Marine Products Export Development Authority, Kochi, India.

[3] Føre, M., Frank, K., Norton, T., Alver, M.O., Alfredsen, J.A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A. and Berckmans, D. 2018. Precision fish farming: A new framework to improve production in aquaculture. *Aquaculture* 495: 803-810.

[4] Li, D., Hao, Y. and Duan, Y. 2020. Smart aquaculture: Application of IoT and AI technologies. *Computers and Electronics in Agriculture* 175: 105531.

[5] Yang, H., Feng, Q., Xia, S., Wu, Z. and Zhang, Y. 2024. AI-driven aquaculture: A review of technological innovations and their sustainable impacts. *Aquaculture* 580: 739902.

[6] Liu, L., Cheng, W. and Kuo, H.W. 2025. Smart sensors and IoT solutions for sustainable agriculture and aquaculture practices. *Sustainability* 17: 5256.

[7] Jawad, H.M., Nordin, R., Gharghan, S.K., Jawad, A.M. and Ismail, M. 2017. Energy-efficient wireless sensor networks for precision aquaculture. *Sensors* 17: 1781.

[8] Ahmed, N., Thompson, S. and Glaser, M. 2023. Wireless communication technologies in aquaculture monitoring systems. *IEEE Access* 11: 45678-45689.

[9] Rahman, M.M., Hasan, M.R. and Islam, M.S. 2023. LoRa-based smart water quality monitoring in aquaculture ponds. *IEEE Access* 11: 38945-38956.

[10] Nguyen, T.H., Tran, P.D. and Nguyen, Q.T. 2022. Big data analytics in smart aquaculture systems. *Information Processing in Agriculture* 9(4): 520-531.

[11] Sharma, R., Patel, M. and Singh, P. 2022. Solar-powered IoT monitoring systems for rural aquaculture. *Renewable Energy* 189: 1443-1454.

[12] Zhang, Y., Li, X. and Chen, W. 2022. Neural network modeling of dissolved oxygen dynamics in aquaculture systems. *Aquacultural Engineering* 97: 102242.

[13] Kim, J., Park, S. and Lee, H. 2022. Automated aeration control system using real-time dissolved oxygen monitoring. *Aquacultural Engineering* 98: 102259.

[14] Cashion, T., Le Manach, F. and Zeller, D. 2021. Economic impacts of precision feeding in aquaculture. *Aquaculture Economics and Management* 25(3): 250-267.

[15] Besson, M., Vandeputte, M. and Kause, A. 2020. Precision feeding and economic performance in aquaculture. *Aquaculture Economics and Management* 24(2): 123-138.

[16] Rahman, M.A. and Islam, M.S. 2022. Machine learning-based disease risk prediction in aquaculture systems. *Aquaculture Reports* 24: 101107.

[17] Zhao, X., Li, Q. and Yang, L. 2023. Deep learning-based fish behavior recognition in aquaculture. *Computers and Electronics in Agriculture* 205: 107563.

[18] Islam, M.S., Rahman, M.A. and Uddin, M.N. 2023. Climate variability impacts and predictive modeling in aquaculture systems. *Climate Risk Management* 41: 100512.

[19] Martins, C.I.M., Eding, E.H. and Verreth, J.A.J. 2023. Digital traceability and sustainability in aquaculture production systems. *Aquaculture Reports* 29: 101463.

[20] Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K.J., Barrett, S., Crépin, A.S., Ehrlich, P.R. and Walker, B.H. 2019. Does aquaculture add resilience to the global food system? *Nature Sustainability* 2: 83-90.

[21] Verdouw, C.N., Wolfert, J. and Tekinerdogan, B. 2020. Smart farming systems architecture and IoT integration. *Agricultural Systems* 178: 102764.

[22] Singh, A., Kumar, R. and Sharma, V. 2022. Hybrid machine learning models for freshwater pond water quality prediction. *Aquacultural Engineering* 96: 102219.

[23] Park, J., Lee, S. and Kim, D. 2021. Biomass estimation in aquaculture using computer vision and AI techniques. *Aquaculture* 540: 736714.