Smart Aquaculture: Technology-Driven Solutions for Sustainable Fish Farming

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ABSTRACT

Smart aquaculture integrates advanced technologies such as artificial intelligence (AI), machine learning, the Internet of Things (IoT), and data analytics to address the limitations of traditional aquaculture and promote sustainable fish farming practices. This article explores the transformative role of smart systems in enhancing productivity, improving fish health, optimizing resource use, and reducing environmental impact. Traditional aquaculture faces significant challenges including water quality management, disease detection, feed efficiency, and labor demands. By leveraging sensor networks, automation, computer vision, and blockchain technology, smart aquaculture enables real-time monitoring, predictive analytics, and transparent supply chains. The study emphasizes the potential of intelligent systems like Recirculatory Aquaculture Systems (RAS), smart sensors, and automated feeding to revolutionize the sector. Furthermore, it highlights the future prospects of intelligent fish farms that operate with minimal human intervention, ensuring higher efficiency and sustainability. Despite certain challenges like cost and technical skill requirements, smart aquaculture presents a viable path toward meeting the rising global seafood demand while preserving aquatic ecosystems.

INTRODUCTION

Aquaculture plays an important part in the economy of culture. The primary element that guarantees efficacy and calibre of aquaculture products is preserving an ecosystem with water. In addition to continuous observation, forecasting, alerting, and risk management of the physical and chemical aspects of the aquaculture environment, smart aquaculture can also monitor fish traits and behaviours in real-time, which allows for the inference of changes in the aquatic environment (Hu *et al.,* 2020). Many industries, including aquaculture, have benefited greatly from modern sophisticated technologies, which have made aquaculture more environmentally friendly, labour-efficient, and productive. Within artificial intelligence (AI), machine learning is a subfield. According to the Food and Agriculture Organization (FAO), there are 564 farmed aquatic species worldwide, including 368 finfish, 88 molluscs, 62 crustaceans, and 32 algae species. Together, finfish, molluscs, and algae account for 450 species, which is approximately 80% of the total species farmed. The idea behind "smart aquaculture" is to grow the aquaculture sector in a sustainable manner while improving output and being friendly with environment (Vo *et al.*, 2021).

Challenges in traditional aquaculture

Aquaculture activities present a number of challenges, such as managing the water quality in the system. Typically, water samples are taken twice daily, in the morning and the afternoon, for instance, when it comes to fish raised in ponds, people are unable to identify diseased fish early on; instead, they must wait for the fish to die or surface before treating them. Similarly, when it comes to the quantity of feed that remains in the pond, people are unable to precisely estimate how much feed is left there, and this food has an impact on the water quality. Counting fish before selling, like seed, requires time and work because each fish must be counted. Aquaculture profitability is impacted by all of the aforementioned challenges. In order to address issues in traditional aquaculture, smart aquaculture seeks to implement smart production modes (Vo *et al*., 2021).

Role of technology in transforming aquaculture

Recirculatory Aquaculture System (RAS) technology allows for recirculation of water, reducing waste and reducing the future environmental impact of aquaculture operations. Artificial intelligence and Machine learning can analyse data from sensors and cameras to analyse water quality, detect disease outbreaks, and optimize feeding and harvesting practices. Internet of Things sensors and devices enable real time monitoring of water quality, temperature, and other environmental parameters, allowing farmers to make data driven decisions. Genomics and Genetics are enabling the development of faster- growing, disease resistant and sustainable aquatic species, specialized software are streamlining aquaculture operations, from feed management and inventory control to financial management and reporting.

Need for Smart Aquaculture

The constant growth in aquaculture density and scale has pushed modern aquaculture techniques to overproduce, which has led to an increase in fish illnesses and a faster rate of water environment imbalance, and deterioration in the aquatic product quality (Wang *et al.,* 2021). Aquaculture still faces many obstacles despite its tremendous growth, such as excessive use of new water, extensive chemical use that negatively impacts the environment and ecosystem, and inadequate management of fish farms that results in large aquaculture losses. Virus-contaminated, unhealthy food is produced by 42% of poorly managed fish farms. Fish kept in high concentrations are frequently kept at low growth rates and have higher feed conversion ratios (FCRs), which raises costs and increases the risk of disease transmission (Kassem *et al.*, 2021). Global demand for seafood is rising, caused by urbanization, population increase, and shifting food habits. Long established aquaculture activities may have detrimental effects on the environment, including habitat destruction and water contamination. Climate change is affecting aquaculture operations with rising water temperatures, changing water chemistry and increased disease prevalence. The species diversity of aquaculture is increasing, with fish, shellfish, and algae accounting for an estimated 40% of the total. Around the world, these species are cultivated in freshwater, brackish water, and marine water, among other water types. Artificial intelligence (AI) and the Internet of Things (IoT) have been increasingly used in aquaculture to solve problems that traditional aquaculture faces. With a number of objectives, they are used in a variety of culture systems, including cages, ponds, hatcheries, and breeding. These include monitoring the water quality and observing the conditions inside cages, ponds, and hatcheries; lowering the frequency of feed delivery to cultured systems; automating the culture systems to save labour; and maximizing the quantity of feed to be supplied for cultured species and the ideal feeding time (Vo *et al.*,2021). Concerns over the industry's impact on the environment have arisen as a result of its explosive growth. Among the many advantages that smart aquaculture techniques can offer are higher output, lower expenses, better environmental sustainability, better fish welfare, more real-time water quality monitoring, and greater fish species diversity. A viable approach to sustainable fish production, smart aquaculture holds promise in tackling major aquaculture issues such disease control, water quality management, environmental effect, and feeding management (Akinsorotan *et al.*, 2024).

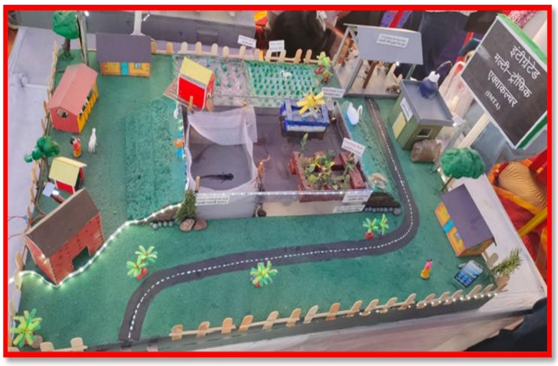

Fig. 1: Smart Aquaculture through Integrated Multi-Trophic Aquaculture (IMTA)

Key Components of Smart Aquaculture

IoT and Sensors: IOT has become a more useful tool in aquaculture because it makes it simpler to send data remotely from real-time decision monitoring. The Internet of Things architecture in aquaculture is divided into four levels: sensing, networking, processing, and application. Sensors collect chemical and physical data (pH, temperature), microcontrollers process it, and networking systems transmit it for real-time display. These technologies, like RAS, Aquaponics, and Bio-Floc, are most commonly used in high stocking culture systems. For continuous, automated, and inexpensive monitoring of processes like feeding and water quality management, this technology is ideal. The use of IoT sensors for aquaculture water quality monitoring increased significantly between 2020 and 2024, enabling better resource management and the growth of aquatic organisms (Flores *et al.*, 2025).

AI and Machine Learning: The analysis of massive volumes of data collected from fish farms has shown great potential for artificial intelligence (AI) capabilities like computer vision and machine learning. Fish growers may learn a lot about feeding habits, development trends, and environmental factors that impact fish health by utilizing AI algorithms. By identifying and forecasting abnormalities, illnesses, and stressors, these algorithms allow for preventative measures to lessen losses and health problems. The creation of intelligent monitoring systems is one of the main uses of AI in aquaculture. These systems continuously collect data on water quality, fish behaviour, temperature, and oxygen levels in real time using a variety of sensors, cameras, and data analytics tools (Mandal & Ghosh 2024).

Automated Systems: Usage of drones, robotics, and feeding automation. In recent years, drones have become more and more popular in aquaculture and fisheries management due to their capacity to, Aquatic resource management and monitoring should be done creatively and innovatively. The aquaculture and fisheries management industries may find these useful in addressing issues including fish population monitoring, water quality assessment, and regulatory enforcement. In addition, they are employed to stop illicit activity in sizable waterways and gather crucial data about them via camera footage and photos (Verma *et al.*, 2023).

Data Analytics: Collecting facts and making decisions in real time. Data mining and machine learning, two overlapping branches of artificial intelligence, employ the ever-increasing volume of data to foresee future problems, assess cause-and-effect correlations, and provide solutions. Despite having many characteristics in common, data mining and machine learning differ in their application breadth, idea, learning capacity, human intervention, and execution. According to Gladju *et al*. (2022), the primary categories of data mining techniques include generalization, characterization, classification, clustering, association, evolution, pattern matching, data visualization, and meta-rule guided mining.

Blockchain Technology: Ensuring traceability and transparency in supply chains. A distributed ledger technology called a blockchain keeps track of transactions involving money, data, or virtual events that participants can view and verify without the need for a central authority. Because blockchains are so standardized, they make it easier for a wide range of actors to interact. Transactions are immutable since no record uploaded to the blockchain can be removed. Numerous industries, including logistics, healthcare, banking, agriculture, and fisheries, are using blockchain in GVCs. Fishing that is illegal, unreported, and unregulated (IUU). In numerous fisheries across the world, IUU fishing leads to overfishing and mislabelling of traded seafood and aquaculture products (Platonava *et al*., 2024).

Benefits of Smart Aquaculture

Smart aquaculture can optimize feeding, watering and harvesting practices, reducing waste and improving productivity. It can also monitor and mitigate environmental effects, like habitat destruction and water contamination. Smart aquaculture optimises growing conditions, such as water temperature and chemistry, to improve yield and quality. It detects early warning signs of disease and mortality, enabling proactive management and reducing economic loss offer real-time information and insights, facilitating data-driven choices and enhancing overall operations.

Fig. 2: Model for Smart Aquaculture

Future prospect of smart aquaculture

The future of smart aquaculture lies in the integration of intelligent systems that aim to "replace man with machine"—automating critical processes such as oxygenation, optimized feeding, disease prevention, and precise harvesting. This shift addresses both labour shortages and the pressing demand for technological innovation in aquaculture. Advanced sensor modules equipped with probes for pH, dissolved oxygen, water temperature, and level monitoring are already being deployed to continuously track aquatic conditions. These systems, paired with Android and web-based applications, allow farmers to remotely manage and optimize pond environments across all types of aquacultures. In India, the adoption of automated feeders and sensor technologies is on the rise. Looking forward, the incorporation of artificial neural networks and machine learning algorithms is essential for enhancing system intelligence and decision-making capabilities (Das *et al*., 2022).

CONCLUSION

Smart aquaculture represents a transformative leap forward in the fisheries sector, offering innovative, technology-driven solutions to the persistent challenges faced by traditional aquaculture. By integrating advanced tools such as IoT, AI, machine learning, automated systems, and blockchain, smart aquaculture enhances real-time monitoring, disease prevention, feeding efficiency, and environmental sustainability. These technologies not only optimize production and reduce resource wastage but also enable data-driven decision-making that significantly improves fish health and product quality. As global seafood demand continues to rise, the adoption of smart aquaculture is no longer optional but essential for ensuring food security, economic viability, and ecological balance. With continued research, infrastructure development, and skill-building, smart aquaculture can lead the way in sustainable and resilient aquatic food systems of the future.

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