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Application of Artificial Intelligence (AI) in Aquaculture for Food Security: An Imperative Review

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ABSTRACT

Aquaculture is a vital component of global food systems, providing a significant source of protein for millions of people worldwide. The increasing global population drives a rising demand for food, particularly fish as a preferred protein source, straining captured fisheries and overfishing has depleted wild stocks thereby emphasizing the need for advanced aquaculture technologies. However, the industry faces numerous challenges, including disease management, water quality monitoring, and feed optimization. Artificial Intelligence (AI) tools like Internet of Things (IoT), machine learning, cameras, and algorithms offer promising solutions to reduce human intervention and challenges, enhancing the efficiency, sustainability, and productivity of aquaculture operations. This review paper examines the opportunities and applications of AI in aquaculture, highlighting its potential to improve food security especially in predictive analytics, automated monitoring, optimization and providing decision support for management decisions on challenges, limitations, and future research directions that would provide a comprehensive overview of AI's role in shaping the future of aquaculture. This review highlights AI's potential to transform aquaculture, increasing productivity, reducing environmental impact, and ensuring food security.

Keywords: Artificial intelligence, aquaculture, food security, predictive analytics, automated monitoring, optimization, decision support

INTRODUCTION

The pursuit of a sustainable food system has prompted the adoption of innovative technologies like Artificial Intelligence (AI) to enhance food security. Artificial Intelligence (AI) encompasses a wide range of disciplines within computer science, with the aim of constructing intelligent machines capable of executing tasks typically demanding human intelligence (Sarker, 2021). The use of AI has become very necessary due to factors that are associated with the intricate and dynamic relationship among social, economic, and environmental indicators that underlie food security (Vinuesa *et.al*., 2020 and Bhagat *et al*., 2022). Despite efforts in the agriculture sector to keep up with the demand of food, the pace of population growth has outstripped agricultural production (Ahmed *et al*., 2024). According to United Nation's estimates, there are over 900 million malnourished people worldwide with one fourth of them being children under the age group of four or five. These young children are particularly vulnerable to the adverse effects of severe Protein and Energy Malnutrition (PEM).

The primary cause of inadequate access to nutrition remains a significant factor contributing to under-nutrition, especially among children in many developing countries (Food and Agricultural Organisation [FAO] 2022). The nutritional value of fish is unquestionable as it is rich in high-quality protein, essential micronutrients and omega-3 unsaturated fatty acids. Notably, fish exhibits more pronounced satiating effects (Ahmed *et al*., 2024) and compared to terrestrial animal proteins like beef and chicken.

Food for developing countries is produced by 80% of smallholder farmers who rely on simple technologies but the rise in agricultural input prices experienced over the last two years, particularly the rising fertiliser costs, has led to higher food prices, and this raises concern about challenges in global food security (Hebebrand and Laborde,2022) (Ritchie 2023). These challenges, such as low crop yields, losses due to weather events (e.g., droughts, floods, and frost), pest and disease incidences, post-harvest losses during storage and transportation, high costs of production, low revenue generation, and uncertainties due to market dynamics among other issues (Elias *et al*., 2019). The surge in food demand and the growth of the global population in recent decades have accelerated the integration of artificial intelligence (AI) technologies into the food sector. In view of the fundamental role of food in human life, the necessity of reducing food waste and improving food management and safety, it has become evident on the capability of AI-supported systems to assess food quality, provide control mechanisms, and perform various operations in Agriculture and specifically in aquaculture (Thapa *et al*., 2023). Aquaculture continues to evolve as a vital component of modern agriculture and environmental management through the facilitation of artificial intelligence of things (AIoT), which integrates artificial intelligence (AI) and internet of things (IoT) to enhance fish farming practices. For instance, digital twins enable real-time monitoring and decision-making, sustainable IoT solutions reduce resource wastage and promote environmental resilience, IoT-based systems improve disease detection and health management, and AIoT-driven water quality inspection systems enhance operational efficiency (Huang, 2025). AIoT applications in aquaculture span a broad spectrum of innovations, including smart feeding systems, water quality management, disease detection, fish biomass estimation, fish behaviour monitoring, organism counting, species segmentation and classification, breeding and growth estimation, individual fish tracking, and automation and robotics. IoT-enabled smart feeding systems utilize data from sensors and underwater cameras to monitor fish behaviour and optimize feeding schedules and quantities.

AI technologies are actively employed in monitoring and managing fish health and growth (Geetha & Bhanu, 2018), thereby leading to improved feed, diminished risk of disease outbreaks, and enhanced overall farm productivity. In the context of the numerous challenges affecting efforts of ensuring food security, AI appears to be a tool that can help develop comprehensive food security management strategies, optimizing crop yields, minimizing losses, and reducing operational costs (Liu *et al*., 2023). AI models offer significant advantages for food security purposes in terms of efficiency, accuracy, consistency, automation, pattern recognition, availability, and scalability (Kutyauripo *et al*., 2023) but they also come with challenges related to data, cost, ethics, and the need for ongoing management. This review therefore focuses on the application of AI to enhance the efficiency and sustainability of the aquaculture industry, particularly in the domains of fish reproduction, feeding, and growth. It aims to enhance knowledge into the myriad applications of AI in aquaculture and potential benefits and address the challenges and limitations in its potential.

AI Uses in Aquaculture

AI uses in aquaculture are effective in traceability, feeding, disease detection, growth prediction, environmental monitoring, market information, and others are key to increasing aquaculture productivity and sustainability. It has provided deep learning techniques in AI disease detection that covers periodical optical monitoring of the fishes in the farm, detecting the onset of any disease, with a minimum time lag. It has provided intelligent feeding technique by calculating the shrimp biomass and determining the appropriate feeding amount by reading the sensors in real time. Intelligent feeding utilizes intelligent equipment that can replace people, reduce labour intensity, reduce risk, and improve work efficiency as well as maintaining water quality and other parameters within the acceptable ranges (Mustapha *et al*., 2021 and Wu *et al*., 2022.

AI is specifically applied in fish breeding with machine learning algorithms, genetic algorithms, and neural networks that gives an improved accuracy in selecting breeding pairs, faster genetic improvement, reduced cost and time of breeding programs and increased disease resistance. In addition, feed optimization also use neural networks, fuzzy logic, decision trees, genetic algorithms that reduces feed wastage, improved growth rates, lower costs, improved sustainability, identification of optimal feeding regimes for different fish species (Chen *et al*., 2022). Furthermore, machine learning algorithms, image recognition, natural language processing are used in disease detection and management as it reveals early detection and diagnosis of diseases, improved accuracy in diagnosis, reduced treatment costs and improved disease management (Darapaneni *et al*., 2022). In the area of water quality management, expert systems, fuzzy logic, neural networks are used to achieve improved water quality management, reduced use of chemicals and antibiotics, improved disease prevention and control and reduced mortality rates (Rastergari *et al*., 2023). Artificial neural networks, machine learning algorithms, acoustic sensors are used in environmental monitoring that provides improved understanding of the impact of environmental factors on fish behaviour, growth and improved sustainability. Robotics, computer vision, machine learning algorithms are deployed in harvesting and processing with benefits in improved efficiency in harvesting, reduced labour costs, improved accuracy in grading and sorting fish thereby reducing waste. In the supply chain management, blockchain and artificial intelligence algorithms are deployed to enhance traceability of fish products, improve efficiency in distribution and increase transparency at reducing fraud. AI utilization has greatly reduced energy consumption, improved the understanding of the impact of aquatic vegetation on fish growth and improved efficiency thereby reducing costs, improved sustainability for increased yield.

Opportunities in AI

AI in aquaculture offers significant opportunities to enhance efficiency, sustainability, and profitability through real-time monitoring and automation. Key applications include optimizing feeding to reduce costs, using computer vision for biomass estimation, monitoring water quality, and early disease detection to improve fish health. AI opportunities emerge as a key in many ways to the development of novel farming methods as it enhances productivity with the use of gadgets that are accessible to provide a more stable environment for the stock. These opportunities are found in the areas of:

i. **Real-Time Water Quality Monitoring:** Real-time water quality monitoring in aquaculture uses IoT sensors to continuously track key parameters—primarily dissolved oxygen, temperature, pH, and turbidity—sending instant data to dashboards. This enables immediate automated responses (e.g., activating aerators) and reduces fish mortality by up to 40% while improving yields by 15–50%. AI that enables highly optimized operations by analyzing data from sensors and cameras to adjust feeding regimes, water quality parameters, and other factors (Lu *et al*., 2022), (Lindholm-Lehto, 2023) thus leading to increased yields. Fish activity can be directly impacted by the water quality due to the fish's high reliance on the aquatic environment. Therefore, monitoring water quality is a crucial problem to consider, particularly in the fish farming industry and AI is increasingly being used to help in this area.

ii. **Fish Health and Welfare Monitoring:** Machine learning and image processing identify behavioural abnormalities or physical signs of disease/parasites, enabling timely interventions and reducing antibiotic use. AI algorithms can identify early signs of disease, parasites, or stress in fish through image analysis and behavior monitoring, allowing for prompt and targeted treatment. A pivotal application of AI in bolstering the health and well-being of fish within aquaculture system (Li *et al*., 2023) which revolves around disease identification and control. Artificial Intelligence (AI) is transforming fish health and welfare monitoring in aquaculture from a reactive, manual process into a proactive, automated, and precision-driven system.

iii. **Automated Monitoring:** AI integrated with robotics and drones helps automate tasks like cleaning cages and monitoring, significantly reducing human intervention. With IoT sensors, cameras, and AI algorithms provide continuous monitoring of crucial environmental factors like water quality, oxygen levels, and fish health, ensuring healthier conditions and reducing risks. For determining fish health and growth rate during the growing stage, biomass is one of the most crucial factors and manual procedure for estimating biomass entails sampling using a fishing net or tray, catching each fish, weighing them individually, and then calculating the biomass. It is a time-consuming and labour-intensive process (Cai *et al*., 2020) (Li *et al*., 2020), which makes it difficult to estimate a larger number of samples for precise biomass estimation. In addition, it gives a higher level of measurement errors brought on by human error and this procedure stresses the fish, which may have negative consequences like growth retardation, nerve damage, and even death.

iv. **Resource Optimization:** AI helps optimize the use of resources like feed, water, and energy by predicting needs and automating adjustments, which reduces costs and minimizes environmental impact. The cost of feeding fish accounts for 40–50 % of the total operational cost of aquaculture, while 60 % of the feed that is dispensed into the aquarium becomes particulates (Ogunlela and Adebayo, 2016). These accumulated particles pollute the water, which uses oxygen to break them down and release ammonia, nitrogen, and other noxious substances that can stunt the growth of fish. Measuring the amount of fish feed intake remains a significant challenge and the amount of feed dispensed to match fish appetite levels plays a significant role in increasing fish productivity. AI and associated software will help to optimize feeding of fish can calculate the ideal feeding schedule and serving size. This would improve feed use, reduce waste, and foster fish growth and health and has a significant impact on fish behaviour, appetite, and growth rates is aquaculture feeding optimization.

v. **Biomass Estimation and Growth Monitoring:** AI-powered cameras (machine vision) analyze fish size, weight, and density in real-time, allowing for better harvesting schedules and improved stock management. These AI tools can accurately estimate fish biomass and monitor growth rates using image and video processing, aiding in farm management and production planning. The optimal temperature for the growth of fish varies, depends on the species of fish reared and maintenance of the optimal temperature, fish farmers can promote faster growth rates and larger fish (Uddin *et al*., 2022). Growth rates, aquaculture, and AI are interconnected as it is a foremost factor used to monitor growth rate. The growth rates of these organisms are critical to the success of the aquaculture industry and AI is used to monitor and manage the growth rates of these organisms, ensuring optimal conditions for growth and maximizing production.

vi. **Behavioral Analysis:** AI can be used to analyze fish behaviour to detect stress or illness, providing insights into their well-being and helping farmers make informed decisions. Fish feeding habits, activity levels, and social relationships can all be affected by temperature conditions. Certain fish species have been found to grow more aggressive in warmer temperatures. Some fish species are known to become more aggressive in warmer temperatures such as tilapia, a common freshwater fish raised for food that has been demonstrated to become more aggressive in warmer temperatures. This is thought to be caused by changes in their metabolism, which can have an impact on how they behave.

Role Of AI in Food Security

Artificial intelligence (AI) enhances aquaculture for food security by optimizing production efficiency, sustainability, and fish health through IoT, machine learning, and imaging systems.

a. **Increased Fish Production:** Machine learning algorithms and computer vision cameras detect abnormal swimming patterns or early signs of pathogens, allowing for early intervention, reducing mortality rates, and decreasing reliance on antibiotics. By improving efficiency and reducing losses due to disease and poor conditions, AI directly contributes to higher and more consistent fish production as fishermen are encouraged for effective reproduction and increase the number of fish in their farm by adjusting the temperature conditions. Freshwater or saltwater habitats can be used for aquaculture, which can use a variety of techniques including tank-based systems, net-pen systems, and integrated multi-trophic aquaculture. It has been studied that in aquaculture, AI can be used to enhance feeding and water quality, regulate fish populations, and prevent disease outbreaks (Prapti *et al*., 2022).

b. **Sustainable Practices:** AI helps optimize water usage in Recirculating Aquaculture Systems (RAS), supporting the expansion of eco-friendly farming in regions with limited water. AI helps reduce antibiotic use by enabling early disease detection and promotes efficient resource management, supporting the long-term sustainability of aquaculture. Aquaculture has the potential to be a sustainable food supply, but it needs to be carefully managed to prevent harm to the environment. It has been reported that AI can be employed to keep an eye on environmental factors like water quality, fertiliser levels, waste reduction, and productivity (Krishnan *et al*., 2021). The use of AI in aquaculture has the potential to boost productivity, promote sustainability, reduce disease outbreaks, and improve growth rates, making aquaculture a more viable and long-term source of food (Mandal and Ghosh, 2023).

c. **Enhanced Food Supply:** As a result of improved productivity and reduced waste, AI contributes to a more stable and abundant supply of fish to meet growing global food demand.

Challenges and Future Directions Oo AI Aquaculture

i. **Data Requirements:** Developing reliable AI models requires large datasets, which are often unavailable or of poor quality in aquaculture environments. A significant challenge is the need for large, high-quality, and labeled data sets for training AI models effectively and a large amount of high-quality data is required to develop effective AI models and algorithms and there is currently a lack of common data formats and protocols to facilitate data sharing across different aquaculture enterprises and research institutions. This limits the application of AI in aquaculture and creates difficulties in collecting and analysing large amounts of data.

ii. **Computational Costs:** High installation and maintenance expenses are significant barriers, particularly for small-scale farmers and in developing regions. Developing and implementing AI systems in aquaculture can be expensive, particularly for smaller-scale operations and there may be a need for investment in infrastructure and technology to support the implementation of AI in aquaculture. As AI systems rely on large amounts of sensitive data, there is a need to ensure that data is securely stored and transmitted, and data privacy is maintained.

iii. **Model Interpretability:** For AI to be fully adopted, its decision-making processes need to be transparent and interpretable to farmers and stakeholders. There is currently a lack of common data formats and protocols to facilitate data sharing across different aquaculture enterprises and research institutions. This limits the application of AI in aquaculture and creates difficulties in collecting and analysing large amounts of data.

iv. **Collaboration:** Continued research and collaboration between scientists, industry, and policy makers are essential to overcome limitations and integrate AI for a more sustainable and effective aquaculture sector. Aquaculture operations involve a wide range of variables, such as water quality, temperature, and feed inputs, that can interact in complex ways to affect fish health and growth. Developing AI algorithms and models that can effectively capture and analyze these complex interactions is a major challenge that will require continued research and development.

WAY FORWARD IN AI APPLICATION FOR FOOD SECURITY

The way forward for Artificial Intelligence (AI) in food security involves moving from isolated pilot projects to a holistic, inclusive ecosystem that integrates on-farm precision technology with supply chain management, while prioritizing accessibility for smallholder farmers.

a. Explainable AI (XAI): Explainable AI (XAI) is a set of techniques and methods that enable human users to understand, trust, and manage the output of machine learning models. Developing AI systems that provide clear justifications for their decisions to increase trust and adoption.

b. Edge Computing & IoT: Edge computing brings data processing and storage closer to IoT devices (sensors, machines) rather than relying on a centralized cloud, enabling reduced latency, higher operational efficiency, and lower bandwidth costs. Implementing AI directly on sensors (edge devices) to provide real-time, autonomous control of water quality and feeding without relying on constant cloud connectivity.

c. Multimodal Data Fusion: Multimodal Data Fusion (MMDF) integrates information from diverse sources—such as text, images, audio, video, and sensors—to create more comprehensive and robust AI models. By combining complementary data, it improves decision-making, predictive accuracy, and situational awareness. Combining data from sensors, cameras, and drones (e.g., combining behavior video with oxygen levels) for improved, holistic insights.

d. **Genomic Selection:** Genomic selection (GS) is a powerful breeding approach that uses dense, genome-wide molecular markers (like SNPs) to estimate the breeding value of individuals, allowing for rapid selection of superior plants or animals. Using AI to analyze genetic data to select fish with better growth rates, disease resistance, and environmental resilience.

CONCLUSION

Data analysis, software development, and aquaculture domain knowledge are just a few of the abilities needed to build and implement AI systems in aquaculture and training educational programmes are required to fill in skill and knowledge gaps. These challenges need to be addressed if aquaculture is to completely benefit from AI by creating effective AI models and algorithms, addressing concerns with data sharing, complexity, cost, privacy, and data security, AI can help aquaculture operations become more sustainable and efficient while also providing a stable and secure supply of high-quality seafood for the growing global population. Because AI makes it possible to regulate fish growth, feeding, and reproduction more effectively and over the long term, the aquaculture industry could undergo a total transformation. Notwithstanding inherent challenges in uses of AI, the future of aquaculture AI looks bright, and the aquaculture industry will likely see an increase in the use of AI as technology grows. Fish production can be managed more effectively and sustainably, providing a consistent and safe supply of premium seafood for food security of the world's growing population.

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