Biological Forum – An International Journal **16(9): 29-38(2024)**

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

The Role of Artificial Intelligence (AI) in Modern Aquaculture: Applications, Advances, Challenges and Future Prospects

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(Received: 18 June 2024; Revised: 16 July 2024; Accepted: 29 July 2024; Published: 14 September 2024)
(Published by Research Trend)

ABSTRACT: Artificial Intelligence (AI) is revolutionizing the aquaculture industry by introducing innovative solutions to enhance productivity, efficiency, and sustainability. Adopting AI technologies such as machine learning, computer vision, and predictive analytics, AI transforms aquaculture operations. It enables precise optimization of feeding practices, comprehensive monitoring of fish health, analyses patterns in fish behaviour, such as swimming speed, schooling behaviour, and feeding activity and effective management of water quality. AI-powered systems deliver real-time data and actionable insights, supporting proactive decision-making, and advancing automated monitoring, disease detection, and environmental management. This leads to significant reductions in operational costs while enhancing fish resilience to diseases through optimized stocking densities and improved management practices.AI enhances productivity and sustainability by enabling accurate monitoring, resource management, and proactive decision-making. Adhering to industry standards and best practices for data security is crucial to mitigate risks and ensure responsible data management. This review paper examines successful AI implementations and case studies, discusses the challenges faced, and explores the future prospects of AI in aquaculture, highlighting its potential to drive growth and sustainability within the industry.

Keywords: Artificial Intelligence, Aquaculture, Fish health monitoring, Feeding optimization, Water quality management, Sustainable aquaculture.

INTRODUCTION

In recent years, the aquaculture industry has witnessed a transformative wave with the integration of artificial intelligence (AI). As demands for seafood continue to rise and traditional methods face challenges, AI emerges as a crucial tool to enhance aquaculture efficiency, sustainability, and productivity (Mustapha *et al.,* 2021). AI has become increasingly relevant in aquaculture research and production in recent years with start-ups and established companies developing new AI-based applications for the industry. AI involves programming that facilitates recognition (images, languages, music, etc.) and decision-making without human supervision (Zhang and Lu 2021). Oxford Languages defines AI as "the theory development of computer systems able to perform tasks that normally require human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages (McNeill *et al*., 1994). The history of AI as it is currently being applied to aquaculture began with something called Fuzzy Logic. In 1965, Lotfi A Zadeh at UC Berkeley published an academic article titled "Fuzzy Sets" (Zadeh *et al*., 1996; Zadeh *et al*., 1996). In 2000, at the University of Texas Medical Branch in Galveston detailed their application of a fuzzy logic-based control system for managing denitrification in a closed recirculating system. Their research aimed to develop a computer-controlled denitrifying bioreactor for a system designed to house squid used in biomedical studies. Over the past two decades, AI technology has evolved significantly across various fields, with many advancements readily adaptable to aquaculture production (Mustapha *et al*., 2021). This chapter explores the diverse applications of AI in aquaculture, its impact on various aspects of the industry, and the potential it holds for the future.

THE STATE OF AQUACULTURE

A. Growth and Challenges

Aquaculture has rapidly emerged as a crucial contributor to the global seafood supply, now accounting for more than half of the seafood consumed worldwide (Anderson *et al.,* 2017). This sector has experienced remarkable growth due to the rising demand for seafood, driven by population growth, increased per capita seafood consumption, and the depletion of wild fish stocks (Merino *et al.,* 2012). The expansion of aquaculture has been instrumental in meeting the nutritional needs of millions and supporting economic development in many coastal and rural regions (Allison, 2011). However, the industry is beset by numerous challenges that threaten its sustainability and long-term viability. Environmental concerns are paramount, as intensive aquaculture practices can lead to habitat destruction, water pollution, and the depletion of natural resources (Sampantamit *et al*., 2020). For example, the discharge of untreated effluents from aquaculture farms can introduce excess nutrients and chemicals into water bodies, causing eutrophication and harming local ecosystems. Disease outbreaks pose another significant challenge, often resulting in substantial economic losses and threatening food security (Leung and Bates 2013). Pathogens such as viruses, bacteria, and parasites can spread rapidly in densely populated aquaculture systems, necessitating the use of antibiotics and other treatments that can have adverse environmental and public health impacts (Okocha *et al.,* 2018). Moreover, the emergence of antibiotic-resistant strains due to overuse of these treatments is a growing concern (Frère and Rigali 2016).

Resource management remains a critical challenge in aquaculture, as these operations demand substantial inputs of feed, water, and energy (Ahmad *et al.,* 2021). Many aquaculture systems rely on wild-caught fish for feed, placing added strain on already overexploited marine resources. Additionally, competition for freshwater between aquaculture and other sectors, such as agriculture and municipal use, can intensify water scarcity issues (Ahmad *et al.,* 2021). Traditional aquaculture methods are increasingly inadequate to meet the growing seafood demand (Diana, 2009). To address these challenges and promote sustainable growth, the industry must innovate. Technological advances such as recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), and selective breeding for disease-resistant species present promising solutions (Lal *et al.,* 2024). Furthermore, enhancing management practices, improving traceability, and adopting more sustainable feed alternatives are essential for developing a resilient and sustainable aquaculture sector (Boyd *et al*., 2024). While aquaculture continues to be a major source of global seafood, addressing environmental concerns, disease outbreaks, and resource management is crucial for its continued success and growth.

B. The Role of Technology

Technological advancements have been crucial in overcoming the challenges faced by the aquaculture sector, transforming traditional practices and boosting efficiency (Subasinghe *et al.,* 2003). These innovations cover various aspects of aquaculture, from water quality monitoring to automated feeding systems, significantly enhancing operational efficiency and sustainability. Advanced monitoring technologies have revolutionized aquaculture management. Sensors and Internet of Things (IoT) devices continuously track essential parameters such as water quality, temperature, pH levels, and oxygen concentration (Prapti *et al*., 2022). This real-time data enables farmers to make informed decisions and quickly address any issues, reducing the risk of disease outbreaks and improving overall farm productivity. Remote monitoring capabilities allow farmers to manage multiple sites from a central location, increasing management efficiency (Seelan *et al.,* 2003).

Automated feeding systems have also greatly improved the precision and efficiency of feed delivery in aquaculture (Zhou *et al.,* 2018). These systems use sensors and data analytics to optimize feeding times and quantities, minimizing waste and ensuring that fish receive the appropriate nutrition. This not only lowers feed costs but also reduces the environmental impact of uneaten feed accumulating in the water. Advanced systems can even customize feeding strategies to meet the specific needs of different species and developmental stages, further enhancing growth and health (Del Vecchio *et al.,* 2022). AI stands out as a game-changer in aquaculture, offering a dynamic approach to problem-solving and operational management (Estim *et al.,* 2023). Machine learning algorithms can analyze vast amounts of data to identify patterns and predict outcomes, such as disease outbreaks or optimal harvesting times (Sarker, 2021). AI-powered image recognition systems can monitor fish behavior and health, detecting anomalies that may indicate stress or disease (Mandal and Ghosh 2024). This proactive approach enables early intervention, reducing mortality rates and improving overall farm performance. Recirculating aquaculture systems (RAS) represent a significant technological advancement in sustainable aquaculture (Ahmed and Turchini 2021). These systems recycle water within the facility, reducing the need for large volumes of freshwater and minimizing environmental discharge.

Recirculating Aquaculture Systems (RAS) technology offers precise control over water quality and environmental conditions, leading to enhanced fish health and growth rates. This innovation facilitates the expansion of aquaculture in regions with limited water resources while reducing the industry's environmental impact. Genetic and biotechnological advancements are also crucial in advancing aquaculture practices (Xiang, 2015). Selective breeding programs are focused on creating disease-resistant and fast-growing strains, thereby increasing the resilience and productivity of farmed species (Oltenacu, 2009). Biotechnology is being leveraged to develop vaccines and probiotics, which enhance disease prevention and decrease the reliance on antibiotics. These developments contribute to more sustainable and efficient aquaculture operations. Blockchain technology is emerging as a valuable tool for improving traceability and transparency throughout the aquaculture supply chain (Tolentino-Zondervan *et al.,* 2023). By providing a secure and unalterable record of every production stage, blockchain technology ensures the authenticity and quality of seafood products from farm to table. This technology helps combat fraud, enhances food safety, and builds consumer trust (Singh and Sharma 2023), so the integration of advanced technologies in aquaculture is driving significant improvements in efficiency, sustainability, and productivity. These innovations are essential for overcoming the industry's challenges and meeting the rising global demand for seafood. As technology continues to advance, it will play an increasingly critical role in shaping the future of aquaculture.

APPLICATIONS OF AI IN AQUACULTURE

A. Data-driven Decision Making

One of the key contributions of AI to aquaculture is its ability to process and analyze vast amounts of data, enabling data-driven decision-making that optimizes the entire production process (Mustapha *et al.,* 2021). The integration of AI with various monitoring devices, such as sensors and cameras, allows for the collection and real-time analysis of critical data points, significantly enhancing the efficiency and sustainability of aquaculture operations (Wang *et al.,* 2021). In modern aquaculture systems, sensors, cameras, and other monitoring devices are deployed to collect real-time data on a wide range of parameters. These include water quality parameters such as temperature, pH levels, dissolved oxygen, salinity, and ammonia levels are continuously monitored to ensure optimal living conditions for the aquatic species (Ubina and Cheng 2022). Cameras and underwater drones capture images and videos of fish, monitoring their movement, feeding patterns, and overall health (Struthers *et al*., 2015). External environmental conditions, such as weather patterns, tides, and water currents, are also tracked to assess their impact on the aquaculture environment. AI algorithms are designed to analyze the collected data, identifying patterns and correlations that might not be immediately apparent to human operators (Meiring and Myburgh 2015). This analysis involves several advanced techniques: Machine learning models are trained on historical data to recognize normal and abnormal patterns. For instance, they can detect deviations in fish behavior that may indicate stress, disease, or suboptimal water conditions. AI can forecast future conditions based on historical and real-time data. Predictive models help anticipate potential issues, such as disease outbreaks or environmental changes, allowing for proactive management (Adegoke *et al*., 2024). AI-powered image recognition and video analysis tools can automatically assess fish health, size, and growth rates (Mandal and Ghosh 2024). These tools can detect physical anomalies or behavioral changes, providing early warnings of potential problems. The insights generated by AI algorithms are used to make informed decisions that optimize various aspects of the aquaculture production process.

AI plays a crucial role in optimizing aquaculture operations by determining the ideal feeding times and quantities based on fish behavior and growth data, which reduces feed waste and boosts growth rates (Li *et al.,* 2020). Automated feeding systems then deliver the precise amounts of feed as recommended. Additionally, AI analyzes behavioral and health data to detect early signs of disease or stress (Barreto *et al.,* 2022), allowing for timely interventions such as adjusting water quality parameters or administering treatments to prevent outbreaks and minimize mortality rates. AI also maintains optimal water quality and environmental conditions by dynamically adjusting aeration, filtration, and other control systems based on real-time data (Monday *et al.,* 2024). This ensures a stable and healthy environment for the aquatic species. Furthermore, AI enhances resource management by optimizing the use of water, energy, and labor, streamlining operations, and reducing inefficiencies (Kristian *et al.,* 2024). These improvements lead to cost savings and a reduced environmental footprint. AI-driven systems continually learn and refine their algorithms as more data is collected and analyzed, resulting in progressively more accurate and effective solutions. This iterative process fosters ongoing improvements in production efficiency, sustainability, and profitability. AI's capability to process extensive data and deliver actionable insights is transforming aquaculture. By facilitating data-driven decision-making, AI enhances feeding strategies, health management, environmental control, and resource allocation. These advancements not only boost the efficiency and sustainability of aquaculture operations but also support the industry's capacity to meet the increasing global demand for seafood.

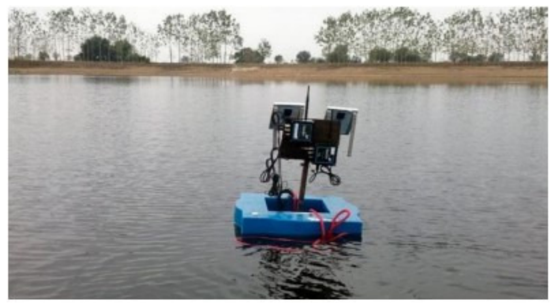

Fig. 1. IoT Device in pond (Source: Niswar *et al.,* 2018).

B. Monitoring and Control Systems

AI-based monitoring systems are transforming aquaculture by enabling continuous and precise surveillance of aquaculture facilities. These advanced systems leverage AI algorithms and various technologies, such as drones and automated control systems, to enhance the health and productivity of aquatic species while ensuring optimal environmental conditions. AI-powered monitoring systems utilize a range of devices to continuously observe and analyze the conditions within aquaculture facilities. Drones equipped with high-resolution cameras and AI algorithms can fly over and underwater to capture detailed images and videos of the aquaculture environment (Ubina and Cheng 2022). They provide a comprehensive view of fish behavior, health, and overall facility conditions. Stationary or mobile underwater cameras monitor fish in their natural habitat, collecting data on their movement, feeding, and interactions. AI algorithms analyze these visual inputs to detect any deviations from normal behavior (Xiang and Gong 2008). A network of sensors measures key water quality parameters, such as temperature, pH, dissolved oxygen, salinity, and ammonia levels. These sensors provide real-time data that AI systems analyze to ensure optimal living conditions for the fish. AI algorithms process the data collected by drones, cameras, and sensors to identify anomalies and potential health issues.

AI plays a pivotal role in optimizing aquaculture operations by analyzing patterns in fish behavior, such as swimming speed, schooling behavior, and feeding activity (Li *et al.,* 2020). Deviations from these normal patterns can signal stress, disease, or suboptimal conditions. AI-powered image recognition systems further enhance monitoring by detecting physical signs of disease, such as lesions, discoloration, or abnormal growths in fish (Shaikh *et al.,* 2021). Early detection through these systems enables prompt intervention, reducing disease spread and minimizing economic losses. Continuous health monitoring facilitates early issue identification, allowing for timely corrective actions, which in turn lowers mortality rates and improves fish welfare.

Automated control systems leverage AI predictions and real-time data to manage various aspects of the aquaculture environment. AI algorithms optimize feeding schedules based on fish growth data, behavior, and environmental conditions (Zhou *et al.,* 2018). Automated feeding systems then deliver precise amounts of feed at optimal times, reducing waste and improving feed conversion rates. AI also manages water temperature by adjusting heating or cooling systems to maintain optimal conditions for different species and life stages (Lowe *et al.,* 2022). This helps prevent temperature-related stress and supports healthy growth. Additionally, AI continuously monitors dissolved oxygen levels in the water, with automated aeration systems adjusting oxygen levels as needed to ensure sufficient oxygen for fish respiration and overall health.

AI-based monitoring and control systems offer a comprehensive approach to aquaculture management by integrating various operational aspects (Ubina and Cheng 2022). These systems balance multiple environmental factors, such as water quality, temperature, and oxygen levels, to create a stable and healthy habitat for aquatic species (Gambin *et al.,* 2021). By optimizing feeding, water usage, and energy consumption, AI enhances resource efficiency and reduces operational costs.AI platforms integrate data from various sources, providing a comprehensive overview of the aquaculture operation. This integrated approach enables better decision-making and more effective management strategies. AI monitoring systems generate real-time alerts and reports for aquaculture managers. When anomalies or critical issues are detected, the system sends immediate alerts to managers, enabling rapid response to potential problems (Mohale *et al.,* 2024). Regular reports summarize key performance indicators, trends, and insights, helping managers track progress and make informed decisions for future improvements. AI-based monitoring and control systems are revolutionizing aquaculture by providing continuous, precise, and intelligent management of aquaculture facilities (Fig. 2). These systems enhance fish health and welfare, optimize resource use, and improve overall operational efficiency, contributing to the sustainability and profitability of the aquaculture industry.

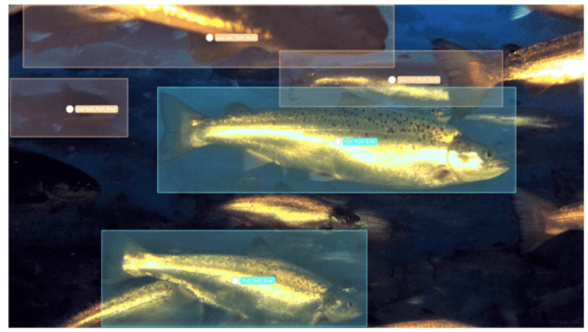

Fig. 2. Salmon being evaluated by Reel Data's health monitoring AI © Reel Data AI.

DISEASE MANAGEMENT AND PREVENTION

AI plays a crucial role in early disease detection within aquaculture systems. By leveraging advanced algorithms and data analytics, AI can identify potential health issues in fish populations before they become widespread, enabling a proactive approach to disease management and significantly reducing the need for reactive measures. This early detection capability is essential for maintaining the health and productivity of aquaculture operations. AI algorithms are trained to recognize subtle changes in fish behavior that may indicate the onset of disease (Li and Du 2022). These changes can include Deviations in normal swimming behavior, such as lethargy, erratic movements, or changes in schooling patterns, which can be early indicators of stress or illness. A reduction in feeding activity or changes in how fish approach feed can signal health issues. AI systems can monitor feeding patterns in real-time and flag anomalies (Mounce *et al.,* 2010).Unusual interactions with the environment, such as increased surface breathing or rubbing against objects, can also be signs of distress or disease (Huntingford *et al*., 2006). AI-powered image recognition systems can detect physical signs of disease by analyzing high-resolution images and videos of fish (Wasik and Pattinson 2024). These signs include the presence of visible sores, lesions, or wounds on fish can indicate infections or parasitic infestations. Changes in coloration, such as pale gills or spots, can be symptoms of various diseases. The appearance of lumps, bumps, or other abnormal growths on the body of fish can be indicative of underlying health problems. AI systems can also monitor vital signs and physiological parameters that provide insights into fish health (Mandal and Ghosh 2024). Changes in the breathing rates of fish can indicate respiratory distress or gill-related diseases. Some advanced systems can measure the heart rates of fish using non-invasive techniques, providing early warnings of stress or illness.

AI significantly enhances early disease detection in aquaculture by analyzing data on metabolic processes such as oxygen consumption and ammonia excretion (Lindholm Lehto, 2023). By integrating behavioral and physiological data with environmental parameters, AI provides a comprehensive view of fish health (Mandal and Ghosh 2024). This integration involves monitoring and correlating critical water quality parameters such as temperature, pH, dissolved oxygen, and ammonia levels with fish health data to identify environmental factors that may contribute to disease. AI systems are adept at detecting and analyzing the effects of sudden environmental changes, such as temperature fluctuations or water contamination, on fish health. The early detection capabilities of AI enable aquaculture managers to implement proactive measures to prevent disease spread (Mandal and Ghosh 2024). By identifying potential health issues at an early stage, managers can take targeted actions such as adjusting water quality parameters, administering treatments, or isolating affected fish to prevent outbreaks. This proactive approach facilitates the strategic use of preventive treatments, including vaccines or probiotics, reducing the reliance on antibiotics and mitigating the risk of resistance development (Bondad Reantaso *et al*., 2023). Additionally, AI insights aid in optimizing stocking densities and other management practices to minimize stress and enhance fish resilience to diseases (Namira *et al.,* 2024). AI systems continuously evolve by analyzing new data and refining their algorithms, which improves the accuracy and reliability of early disease detection over time. This iterative learning process strengthens the resilience of aquaculture operations against emerging health challenges. AI's ability to detect subtle changes in fish behavior, appearance, and vital signs is crucial for early disease detection in aquaculture systems. This proactive approach reduces the impact of diseases, minimizes the need for reactive measures, and supports the overall health and productivity of aquaculture operations.

AI-driven precision treatment methods are revolutionizing disease management in aquaculture. By leveraging advanced data analytics and machine learning algorithms, these methods enable targeted medication and vaccine administration based on individual fish health profiles. This approach reduces the overall use of pharmaceuticals and minimizes the risk of antibiotic resistance, leading to more sustainable and effective disease management practices. AI systems can create detailed health profiles for individual fish by analyzing a variety of data points, including behavior, physical appearance, and physiological parameters (Xu *et al.,* 2006). These profiles help in identifying specific health needs and tailoring treatments accordingly. Continuous monitoring of swimming patterns, feeding behavior, and interactions with the environment provides insights into the well-being of each fish (Mandal and Ghosh 2024). High-resolution imaging and video analysis detect signs of disease, such as lesions, discoloration, and abnormal growths, at an early stage (Mandal and Ghosh 2024). AI can assess vital signs and metabolic indicators to identify health issues that may not be visible externally. AI-driven systems enable precise delivery of medications to individual fish or specific groups showing signs of illness (Gholap *et al.,* 2024). This targeted approach offers several benefits. By administering medications only to fish that need them, the overall use of pharmaceuticals is significantly reduced. This not only lowers costs but also minimizes the environmental impact of drug residues. Targeted treatment ensures that fish receive the correct dosage at the right time, improving the efficacy of medications and accelerating recovery. Targeted medication reduces the need for whole-pond treatments, which can stress fish and disrupt the aquaculture environment.

AI technology is also advancing the administration of vaccines in aquaculture, leading to more effective disease prevention strategies (Tammas *et al.,* 2024). AI systems can identify fish that are most at risk of disease and ensure they receive timely vaccinations. This approach maximizes the protective benefits of vaccines while minimizing the use of biological products. AI can analyze data to determine the optimal timing for vaccine administration, taking into account factors such as fish age, health status, and environmental conditions. Automated vaccination systems reduce the need for manual handling of fish, which can cause stress and increase the risk of injury. AI-driven systems continuously monitor the health of treated fish to assess the effectiveness of medications and vaccines (Russo *et al.,* 2020). AI analyzes real-time data on fish behavior, appearance, and physiological parameters to evaluate the response to treatment. Based on monitoring results, AI systems can dynamically adjust treatment plans, ensuring that fish receive the most appropriate and effective care. Continuous monitoring helps detect early signs of antibiotic resistance, allowing for timely intervention and the implementation of alternative treatment strategies. The precision treatment approach supported by AI contributes to more sustainable disease management practices in aquaculture (O'Donncha and Grant 2019). By minimizing the use of antibiotics and targeting their application, the risk of developing antibiotic-resistant strains is significantly lowered. Precision treatment ensures that fish receive the care they need without unnecessary interventions, promoting overall health and welfare. Targeted use of pharmaceuticals and biological products reduces the environmental footprint of aquaculture operations, protecting surrounding ecosystems. AI-driven precision treatment is integrated with broader aquaculture management systems, enhancing overall operational efficiency (Mandal and Ghosh 2024). AI systems combine health data with environmental and operational parameters to provide a holistic view of aquaculture operations. Aquaculture managers can make more informed decisions based on detailed insights from AI analyses, optimizing both disease management and overall production processes. Precision treatment contributes to the efficient use of resources, including feed, water, and labor, reducing costs and improving sustainability. In conclusion, AI-driven precision treatment methods are transforming disease management in aquaculture by enabling targeted medication and vaccine administration based on individual fish health profiles. This approach reduces pharmaceutical use, minimizes antibiotic resistance, and promotes sustainable and effective disease management practices, ultimately enhancing the health and productivity of aquaculture operations.

IMPROVING FEED EFFICIENCY

AI significantly contributes to optimizing feed efficiency in aquaculture by analyzing data on fish growth rates, feeding patterns, and nutritional requirements. Smart feeding systems powered by AI adjust feed portions and schedules to ensure that each fish receives the optimal amount of feed. This not only improves growth rates but also reduces waste and minimizes environmental impact. AI systems track the growth rates of individual fish or groups, using data collected from sensors and cameras. By analyzing this data, AI can determine the precise nutritional needs of the fish at different stages of their development (Barbedo, 2022). Monitoring feeding behavior helps AI systems identify the most efficient feeding times and methods (Moutaouakil and Falih 2024). For example, AI can detect when fish are most active and hungry, allowing for more effective feed distribution. AI algorithms consider the specific dietary needs of different fish species and life stages, ensuring that the feed provided meets their nutritional requirements for optimal growth and health (Mustapha *et al.,* 2021). AI-powered feeders adjust the amount of feed dispensed based on real-time data. This precision ensures that fish receive just the right amount of feed, reducing waste and preventing overfeeding (Zhang *et al*., 2024). AI determines the optimal feeding schedules and timing feedings to align with the natural behaviors and metabolic needs of the fish (Wei *et al*., 2021). This can lead to more efficient feed conversion and better growth rates. AI systems continuously monitor fish behavior and environmental conditions, making real-time adjustments to feeding strategies as needed (An *et al.,* 2021). This dynamic approach ensures that feeding practices remain efficient and effective under varying conditions. By providing the right amount of feed at the right times, AI-driven feeding systems enhance the growth rates of fish, leading to higher productivity and profitability (Rather *et al.,* 2024). Precision feeding minimizes feed wastage, which not only lowers feed costs but also reduces the accumulation of uneaten feed in the water, preventing water pollution and improving overall water quality (Fig. 3-4). Optimized feeding practices reduce the environmental footprint of aquaculture operations by decreasing nutrient runoff and minimizing the impact on surrounding ecosystems (Munguti *et al.,* 2020).

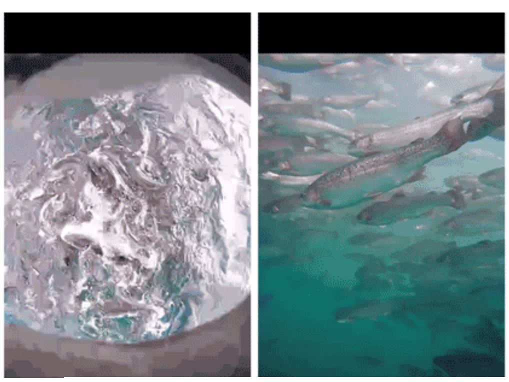

Fig. 3. Feeding sea bream with Umitron's AI solution © Umitron. Umitron's system utilizes real-time monitoring of swimming behavior to make decisions regarding when and how much feed to dispense to each fish cage.

Fig. 4. Uneaten feed detected by AKVA observe system (Minapoli, 2021).

A. Sustainable Feed Formulation

AI algorithms are increasingly pivotal in the development of sustainable and nutritious feed formulations for aquaculture. By leveraging sophisticated data analysis and predictive modeling, AI optimizes feed recipes to meet the specific needs of fish species while minimizing environmental impacts. This approach contributes to a more sustainable and efficient aquaculture industry. AI enables the creation of customized feed formulations based on the precise nutritional requirements of different fish species and growth stages (Mandal and Ghosh 2024). Different fish species have varying nutritional needs, and AI algorithms analyze data on species-specific requirements, such as protein, lipid, and carbohydrate levels, to develop feeds that meet these needs effectively. As fish progress through different growth stages, their nutritional requirements change. AI systems adjust feed formulations to cater to these evolving needs, ensuring optimal growth and health at each stage of development.

AI algorithms assess and optimize the use of feed ingredients to balance nutrition, cost, and sustainability (Mustapha *et al.,* 2021). For example, AI evaluates alternative protein sources, such as plant-based proteins, insect meals, or single-cell proteins, which can replace traditional fishmeal (Hadi and Brightwell 2021). These alternatives often have a lower environmental impact and reduce pressure on wild fish stocks. AI also helps identify sustainable sources of lipids, such as algae-based oils, to replace fish oils in feed formulations, contributing to reduced overfishing and environmental degradation. Additionally, AI optimizes the use of by-products and waste materials from food processing industries by incorporating them into feed formulations in a way that minimizes waste and reduces the environmental footprint. AI algorithms consider the environmental impact of feed ingredients and production processes to develop more sustainable feeds (Luna *et al*., 2022). AI performs life cycle assessments (LCAs) of feed ingredients to evaluate their environmental impact, including factors such as land use, water consumption, and greenhouse gas emissions (Nabavi-Pelesaraei *et al.,* 2018). This analysis helps select ingredients with a lower environmental footprint. AI identifies and promotes the use of ingredients and practices that optimize resource use, such as reducing water and energy consumption during feed production. By enhancing fish health and performance, AI-driven formulations contribute to more sustainable aquaculture practices (Mandal and Ghosh 2024). AI identifies and incorporates functional ingredients, such as prebiotics, probiotics, or immune-boosting compounds, that support fish health and reduce the need for antibiotics and other medications. By optimizing nutrient profiles and feed formulations, AI improves feed conversion ratios (FCR), leading to faster growth and better feed utilization, which contributes to higher productivity and lower environmental impact. AI algorithms also balance nutritional quality with economic considerations to ensure that feed formulations are cost-effective (Patel *et al.,* 2022). AI analyzes ingredient costs and availability to create economically viable feed formulations that do not compromise nutritional quality. It monitors market trends and ingredient price fluctuations to adjust feed formulations accordingly, ensuring that feeds remain affordable and competitive. AI systems continuously learn from new data and feedback, allowing for ongoing improvements in feed formulations (Lafont *et al.,* 2019). As new research and data become available, AI algorithms update feed formulations to incorporate the latest nutritional insights and sustainability practices. AI also tracks the performance of feed formulations in real-world aquaculture settings, using this data to refine and enhance future formulations.AI-driven feed formulation is integrated with broader aquaculture management systems to enhance overall operational efficiency (Mohale *et al.,* 2024). AI integrates data on fish health, environmental conditions, and operational parameters to develop comprehensive feed strategies that align with overall farm management goals. Aquaculture managers benefit from AI's insights and recommendations, leading to more informed decisions that improve both feed quality and sustainability. AI plays a crucial role in developing sustainable and nutritious feed formulations for aquaculture. By optimizing ingredient use, considering environmental impacts, enhancing fish health and performance, and balancing cost considerations, AI contributes to a more sustainable and efficient aquaculture industry. This approach supports the long-term viability of aquaculture and helps address global challenges related to seafood production and environmental sustainability.

CHALLENGES AND ETHICAL CONSIDERATIONS

The increasing reliance on AI in aquaculture introduces significant challenges related to data security and privacy. The collection, storage, and analysis of vast amounts of data are crucial for AI systems to function effectively, but this data can be sensitive and susceptible to various threats. Ensuring robust cybersecurity measures is essential to protect against potential breaches and maintain trust in AI technologies. AI systems in aquaculture collect various types of data, including environmental parameters (e.g., water quality, temperature), operational data (e.g., feeding schedules, growth rates), and potentially sensitive business information (Biazi and Marques 2023). The volume and variety of data collected can include both structured data (e.g., sensor readings) and unstructured data (e.g., video feeds), complicating data management and security. Centralized data storage systems can be vulnerable to attacks, while decentralized systems can be more challenging to secure due to their complexity (Shen *et al.,* 2021). Ensuring data is encrypted both in transit and at rest is vital to prevent unauthorized access and data breaches (Shukla *et al.,* 2022). AI systems can be targeted by hackers seeking to steal sensitive information or disrupt operations. Robust firewalls, intrusion detection systems, and regular security audits are necessary to mitigate these risks. Ensuring the integrity of data is crucial, as corrupted or tampered data can lead to incorrect AI predictions and decisions, potentially harming fish health and farm productivity (Vardhan *et al*., 2024). Compliance with data protection regulations, such as GDPR in Europe or CCPA in California, is essential to ensure the privacy and security of personal and sensitive data (Bakare *et al.,* 2024). Adhering to industry-specific standards and best practices for data security can help mitigate risks and ensure responsible data management.

As AI becomes more integrated into aquaculture, several ethical considerations arise regarding its impact on the environment, animal welfare, and local communities. Addressing these ethical concerns is crucial for implementing responsible AI practices that promote sustainability and social responsibility.AI can enhance sustainability by optimizing resource use and reducing environmental impact (Kristian *et al.,* 2024). However, it is essential to ensure that AI technologies do not inadvertently cause ecological harm, such as through the overuse of automated systems that may disrupt natural habitats. Striking a balance between improving operational efficiency and conserving natural resources is key to sustainable aquaculture (Boyd *et al.,* 2020). AI systems that monitor fish health and behavior can significantly improve animal welfare by enabling early detection and treatment of diseases. However, it is important to ensure that these technologies do not cause undue stress or harm to the animals. Ensuring that AI-driven practices align with ethical standards for the humane treatment of fish is crucial (Chisom *et al.,* 2024). This includes considerations around stocking densities, feeding practices, and handling procedures. The adoption of AI and automation in aquaculture could potentially displace workers and impact local communities that rely on traditional aquaculture practices for their livelihoods. It is important to consider the socioeconomic impacts and provide support for workforce transitions. Engaging with local communities and stakeholders is essential to ensure that AI implementation in aquaculture is inclusive and benefits all parties involved (Bremer *et al.,* 2016). Ensuring that AI algorithms are transparent and understandable is crucial for accountability. Stakeholders should be able to understand how decisions are made and trust that AI systems are used responsibly. Developing and adhering to ethical AI frameworks can guide the responsible deployment of AI in aquaculture, ensuring that ethical considerations are integrated into decision-making processes (Georgopoulos *et al.,* 2023). Adopting a holistic approach that considers environmental, social, and economic factors is essential for the long-term sustainability of AI in aquaculture. Regularly assessing and updating AI practices and policies to reflect evolving ethical standards and societal values is necessary to maintain responsible AI use (Díaz-Rodríguez *et al*., 2023). while AI offers significant benefits for aquaculture, addressing data security and privacy challenges, as well as ethical considerations, is crucial for responsible implementation. Ensuring robust cybersecurity measures, complying with data protection regulations, promoting sustainability, enhancing animal welfare, supporting local communities, and maintaining transparency and accountability are essential components of ethical AI practices in the aquaculture industry.

CONCLUSIONS

Artificial intelligence has emerged as a transformative force in the aquaculture industry, offering solutions to longstanding challenges and paving the way for a more sustainable and efficient future. Through advancements in machine learning, computer vision, and predictive analytics, AI enables precise monitoring, optimal resource management, and proactive decision-making, significantly enhancing productivity and sustainability in aquaculture operations. Quickly, integrating artificial intelligence (AI) with modern aquaculture is a game-changing advance in boosting productivity and efficiency rates of the industry while maintaining its sustainability. AI for fish farms according to several studies, AI can be used not only in real-time water quality and fish health monitoring but also feeding regime as well growth pattern prediction. The benefits of these improvements reduce costs and, more importantly, mitigate negative environmental impacts related to unsustainable problems such as overfishing or depletion. With aquaculturists able to use machine learning and smart sensors as part of AI technologies, they can help make data-driven decisions. Moreover, the ability of AI to aid in disease diagnosis and timely feed management underscores its use towards sustainability aquaculture practices.As technology advances, AI integration in aquaculture is expected to evolve, addressing emerging issues such as climate change impacts, disease outbreaks, and market demands. Continued innovation and adoption of AI will contribute to the growth of a resilient and responsible industry, ensuring the sustainable production of seafood to meet the needs of a growing global population. The ongoing collaboration between researchers, industry stakeholders, and policymakers will be crucial in unlocking the full potential of AI in aquaculture and achieving a balance between economic growth and environmental stewardship.

Despite such promising advancements, challenges exist in the extensive use of AI in aquaculture. Such as the cost of rolling an AI solution, need for technical knowledge or integrating it into existing system complexities in order to leverage its benefits fully. At every step, ongoing R&D and technology integration with support of aquaculture stakeholders will be necessary to address these challenges. Exciting times lay ahead, as the aquaculture industry sets off to grow at scale; fuelled by AI-disruptions that have potential to significantly increase efficiency and sustainability across species. As seafood needs explode around the globe, we will increasingly depend on AI to satisfy them sustainably. Continued development of AI technologies for aquaculture will eventually result in more robust and adaptive farming systems, ultimately contributing to a more sustainable food supply chain.

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How to cite this article: Inab Majeed Bala, Tabish Farooq, Gowhar Iqbal, Arya Singh and Maharshi Limbola (2024). The Role of Artificial Intelligence (AI) in Modern Aquaculture: Applications, Advances, Challenges and Future Prospects. *Biological Forum – An International Journal, 16*(9): 29-38.