



Review Paper

Application of Artificial Intelligence (AI) in Aquaculture: A Review

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Abstract

Over the past 20 years, AI technology has rapidly advanced in various fields, including aquaculture. Artificial intelligence is being tested and implemented in aquaculture to enhance feeding efficiency, estimate biomass, track growth, diagnose diseases early, and monitor and manage environmental conditions especially in recirculating aquaculture systems (RAS). These advancements in sensor and processing technologies enable many repetitive tasks in modern aquaculture to be performed with reduced labour and improved animal welfare. This review explores the potential applications of AI in aquaculture practices, aiming to increase production while minimizing disease and environmental losses. AI contributes to several areas, including disease management, feeding, water quality management, genetics and breeding, and the conservation of endangered species.

1. Introduction

In the twenty-first century, the global population has experienced considerable growth. While the agricultural sector is diligently striving to meet the increasing demand for food, this rapid population expansion continues to surpass agricultural output (Ahmed et al., 2024). Consequently, the distribution of essential nutrients such as protein, fat, and calories in people's diets has become increasingly imbalanced (Pradhan et al., 2019). The United Nations estimates that more than 900 million individuals worldwide are undernourished, with children under the age of four or five accounting for a quarter of those affected. These young children are especially vulnerable to the detrimental effects of severe malnutrition, including protein-energy malnutrition (PEM). Limited access to nutrient-dense foods continues to be the main cause of undernutrition, which poses a serious problem for children in many developing countries (UN, 2010). Fish has become a major source of protein in many developing nations in recent decades (Ahmed and Ahmad, 2020; FAO, 2020; Ahmad et al., 2021; Ahmad et al., 2021a, b; Ahmad et al., 2022). Fish is known for its many nutritional advantages, including omega-3 unsaturated fatty acids, high-quality protein, and vital

minerals. Notably, compared to terrestrial animal proteins like beef and chicken, fish has more noticeable satiating effects (Uhe et al., 1992). About 80% of people in wealthy countries get less than 20% of their animal protein from fish, while about 60% of people in developing countries get at least 30% of their animal protein from fish (FAO, 2022). Additionally, some Asian nations exhibit a comparatively greater reliance on fish (Delgado, 2003). Since a large percentage of the world's population depends on fish for survival, fish and fish-related products make up a large portion of their diets (Minar et al., 2012; Chakraborty et al., 2015; Gandotra et al., 2017). Aquaculture, or the farming of aquatic organisms, is becoming more and more important in addressing food security and satisfying the rising global demand for animal protein. As the aquaculture industry grows, it must address a number of issues, such as maintaining the wellbeing and health of farmed fish populations and maximizing their growth. Sustainable aquaculture practices aim to mitigate negative environmental impacts while enhancing productivity and profitability (Austin et al., 2022). In this context, artificial intelligence (AI) has demonstrated significant potential for improving fish farming productivity and health monitoring, contributing to the sustainability of aquaculture operations (Chen et al., 2023).

AI encompasses the study and application of computer systems designed to perform tasks typically requiring human intelligence, such as learning, problem-solving, and decision-making (Dellermann et al., 2019). In aquaculture, AI methodologies offer opportunities for data analytics, predictive modeling, real-time monitoring, and decision support systems. These developments have the potential to greatly improve fish growth and health management and comprehension (Mustapha et al., 2021). Within the context of sustainable aquaculture, this review offers a thorough examination of the function of artificial intelligence in tracking fish growth and health. Aquaculture methods are changing to maximize fish growth rates while minimizing feed inputs, energy use, and environmental effects. Fish growth and health are actively monitored and managed by AI technologies, which enhances feed efficiency, lowers the risk of disease outbreaks, and increases overall farm productivity.

In aquaculture, artificial intelligence (AI) is being used more and more to analyze sensor and camera data, track fish behavior, detect signs of illness or stress, automate fish length and weight measurements, and optimize feeding schedules (Barreto et al., 2022; Føre et al., 2018; Tonachella et al., 2022). Researchers can create predictive models that identify early indicators of illness or stress in fish by using AI algorithms on this data (Gladju et al., 2022). Sharma and Kumar (2021) stress the importance of combining sensors, biosensors, and AI technologies to reduce dependence on antibiotics and other medications. Furthermore, artificial intelligence (AI) helps create customized feeding schedules that address each fish's unique nutritional requirements, increasing growth rates and improving general health and wellbeing (Kaur et al., 2021). AI can enhance fish reproduction management by developing predictive models that pinpoint ideal spawning and egg production conditions (Chapman et al., 2014; Migaud et al., 2013). Early warning systems, behavioral analysis, and disease detection and diagnosis tools are examples of AI-based techniques that offer resources for quick and precise disease identification, allowing for prompt interventions that help stop the spread of infections (MacIntyre et al., 2023). AI can also help with real-time environmental monitoring, which makes it possible to identify changes in water quality indicators before they have a negative impact on fish health.

This paper seeks to explore various AI methodologies, such as machine learning, computer vision, and data analytics that have been applied in aquaculture research and industry. It will investigate how these technologies have improved feed management and optimization, enabled early disease identification and diagnosis, and increased fish growth rates. The article will also examine the role of AI in water quality control and environmental monitoring within aquaculture systems. Ultimately, the implementation of AI in aquaculture has the potential to enhance productivity, promote global food security,

and support the sustainable production of seafood.

2. Type of Artificial Intelligence (AI)

Artificial intelligence (AI) refers to the simulation of human cognitive abilities within computers designed to perform tasks such as perception, reasoning, learning, and decision-making—functions that typically require human intelligence (Xu et al., 2021). AI is an extensive field encompassing numerous subfields and applications, as well as various types of artificial intelligence (Figure 1).

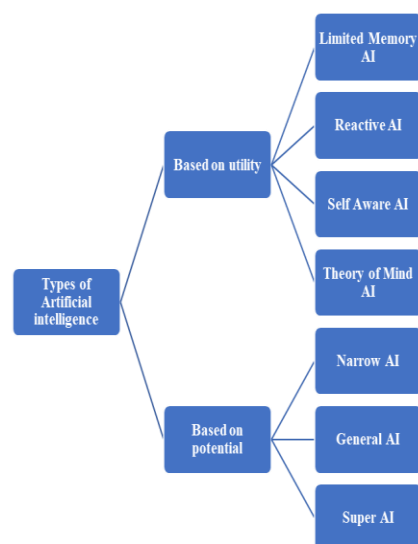


Figure 1: Different Types of Artificial Intelligence (AI)

2.1 Based on utility

Reactive AI: This type of AI is designed to respond to specific circumstances or inputs but cannot learn from past experiences or anticipate future events (Sarker, 2022).

Limited Memory AI: This AI can learn from past experiences and make decisions based on that knowledge, though it has limited memory and cannot process vast amounts of data (Xu et al., 2021).

Theory of Mind AI: This kind of artificial intelligence is capable of understanding the thoughts, feelings, and intentions of other agents, making it useful for applications such as social robots.

Self-Aware AI: This type of AI is self-aware, meaning it recognizes its own abilities and limitations.

2.2 Based on potential

Narrow AI: Often referred to as weak AI, Narrow AI is designed to perform a specific task. It advances within a defined subset of intellectual capabilities. As machine learning and deep learning techniques evolve, specialized AI applications are increasingly becoming part of our daily lives (Sarker, 2022).

General AI: Also known as strong AI, General AI has the

potential to understand and learn any intellectual task that a human can perform. This capability allows a machine to utilize knowledge across various contexts. However, researchers have yet to achieve strong AI, as they still need to devise a method for encoding a complete set of cognitive functions into machines to enable consciousness.

Super AI: This concept surpasses human intelligence, functioning more effectively than a person in any given task. The idea of artificial super intelligence envisions AI evolving to a stage where it not only comprehends human emotions and experiences but also develops its own emotions, needs, beliefs, and desires. The future of super AI remains uncertain. For it to exist, it must exhibit critical abilities such as reasoning, problem-solving, judgment, and autonomous decision-making (Xu et al., 2021; Sarker, 2022).

3. Application of AI in Fisheries and Aquaculture

Aquaculture, which refers to the production of fish, crustaceans, mollusks, and other aquatic animals in controlled environments, has significant potential for transformation through artificial intelligence (AI) (Chauhan and Mishra 2022). AI technologies can enhance various aquaculture methods in several ways. Here are a few applications of AI in the field of aquaculture (Figure 2):

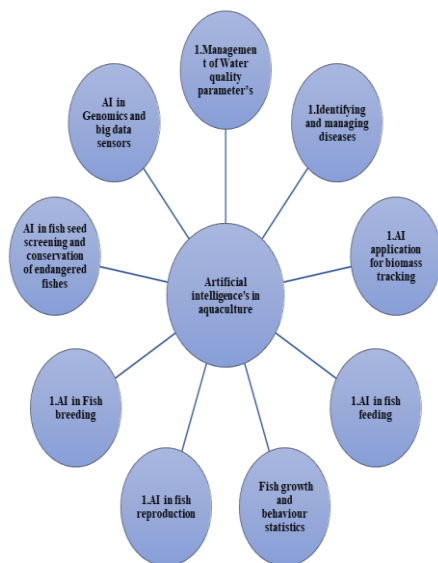


Figure 2: Application of AI in Fisheries and Aquaculture

Data interpretation and forecasting: Artificial Intelligence possesses the ability to analyze vast amounts of data collected from various sources, such as feeding systems, water quality monitors, and environmental sensors. By employing machine learning algorithms to identify patterns and correlations within this data, aquaculturists can make informed, data-driven decisions (O'Donncha et al., 2021). For instance, AI can forecast optimal growth rates, feeding schedules, disease outbreaks, and environmental conditions, ultimately enhancing productivity.

Surveillance and observation: Cameras equipped with

artificial intelligence and image recognition technology can monitor the behavior, eating patterns, and overall health of fish. By analyzing real-time video feeds, AI systems can detect irregularities or signs of stress within the fish population (Mustapha et al., 2021). This capability facilitates early intervention, enabling prompt treatment of infections or adjustments to feeding schedules.

Management of water quality: Aquatic species rely on optimal water quality for their growth and well-being. Key parameters such as temperature, pH, dissolved oxygen, and nutrient levels can be continuously monitored using AI systems (Kaur et al., 2023a). By integrating sensor data with AI algorithms, aquaculturists can mitigate the risk of fish mortality and enhance overall production by detecting deviations from ideal conditions and implementing corrective measures in real time (Gladju et al., 2022).

Inventory control: Artificial intelligence (AI) can assist aquaculture facilities in managing their inventories and stock levels more efficiently. By analyzing growth rates, feeding patterns, and market demand, AI algorithms provide valuable insights into optimal stocking densities, harvest times, and production scheduling (Gladju et al., 2022). This technology enables aquaculturists to maximize profitability and enhance resource utilization.

3.1. Management of Water quality parameters

Effective monitoring is essential for the success of aquaculture operations due to the numerous factors that affect water quality (Lindholm-Lehto, 2023). In order to ensure sustainable water management, a number of factors are essential. Because fish are so reliant on their aquatic habitat, the water's quality can have a big influence on how they behave. As a result, keeping an eye on water quality is crucial, especially in the fish farming sector (Arafat et al., 2020). To help with this endeavor, artificial intelligence is being used more and more (Lu et al., 2022).

The purpose of this section is to explain how aquaculture systems can use artificial intelligence (AI) to monitor water quality. AI systems can spot patterns and anomalies that might point to possible problems with water quality by examining data gathered from sensors that measure variables like temperature, pH, dissolved oxygen, and ammonia concentrations (Dupont et al., 2018; Zhao et al., 2021; Khurshid et al., 2022). This ability allows farmers to take precautions before the fish suffer any harm. AI-powered water quality monitoring devices can evaluate several parameters in real-time, offering more precise and timely information than conventional manual monitoring methods (Javaid et al., 2022). This real-time monitoring lowers the risk of fish mortality and other unfavorable outcomes by enabling producers to react quickly to changes in water quality.

Saeed et al. (2022) also indicated that these systems can analyze historical data on water quality alongside other factors, such as feeding schedules and weather trends.

Furthermore, AI algorithms can proactively notify farmers of potential changes in water quality by predicting their likelihood. Gunda et al. (2018) developed a mobile software platform using artificial intelligence to detect bacterial contamination in water, utilizing a fast, cost-effective test device known as a mobile water kit. AI algorithms can also assist farmers in optimizing water quality parameters that are specific to the needs of the aquaculture species under cultivation (Chiu et al., 2022).

Since it directly affects the development and well-being of aquatic organisms, temperature is an essential component of aquaculture (Mugwanya et al., 2022). By evaluating data from temperature sensors, AI systems can continuously monitor the water temperature in fish farms. By using this method, the system can spot patterns and anomalies in temperature data and notify farmers in real time when the temperature deviates from the ideal range for the particular species being grown (Yang et al., 2021). Because of this, farmers are able to quickly identify temperature changes and take the necessary action to keep the fish healthy and growing (Mustafa et al., 2016; Joseph et al., 2019; Chiu et al., 2022). Furthermore, by providing useful insights into how environmental changes impact fish, artificial intelligence algorithms that continuously monitor temperature can assist farmers in mitigating potential problems resulting from temperature variations (Fire et al., 2018). AI algorithms can access data from a variety of environmental factors, such as weather patterns, feed management, and water quality, to provide a thorough overview of the conditions at the fish farm (Lafont et al., 2019). AI systems can provide farmers with accurate and comprehensive insights into how various environmental factors can affect fish health and growth by combining this data (Niloofar et al., 2021). This ability can help farmers make informed decisions to run their fish farms as effectively as possible and to minimize any problems brought on by temperature swings or other environmental factors (Gladju et al., 2022). These studies' conclusions unequivocally show that AI systems can give fish farmer's useful information.

3.2. Identifying and managing diseases

Since early detection of an epidemic allows for prompt intervention and reduces the spread of illness, effective aquaculture heavily depends on the identification and control of diseases. Research has shown that artificial intelligence is a useful tool for examining fish behavior to identify any unusual situations or activities, especially when neural network models are used. Improving fish health and welfare through disease detection and management is a crucial use of AI in aquaculture systems. AI is increasingly being used in aquaculture operations, particularly for fish disease diagnosis and treatment (Li et al., 2023). AI can identify symptoms of illness or stress in fish by analyzing data from sensors and cameras. For example, cameras can keep an eye on fish behavior to spot any changes that

might point to stress or disease, like decreased activity or irregular swimming patterns.

According to Chen et al. (2022) reported that the integration of AI has shown promise in advanced disease diagnosis based on fish behavior and external appearance. Additionally, this detection system's analysis unit and evaluation mechanism make use of photos taken by sensors or underwater cameras via the cloud. This technology gives artisan farmers important extra time to investigate different approaches to management (Darapaneni et al., 2022). Analyzing fish photos for particular disease markers is one creative way to use AI for fish disease detection (Yang et al., 2021). By placing cameras all over fish farms, operators can use visual analysis of fish photos to detect disease symptoms like discoloration, unusual behavior, or lesions (Nik Zad, 2013; Chan et al., 2022). In addition to lowering the need for antibiotics, this approach lowers the chance of epidemics, allowing farmers to identify and treat illnesses earlier. Aquaculturists are therefore in a better position to identify fish diseases early on, which enhances treatment results and reduces the likelihood that the diseases will spread to other fish populations.

Additionally, AI can be very helpful in identifying disease indicators in water quality data (Setiyowati et al., 2022). Fish health depends on a number of water quality factors, such as temperature, pH, and dissolved oxygen levels, which can also indicate the presence of diseases. This water quality data can be processed by AI algorithms to find patterns that might indicate disease activity (Nayan et al., 2021). Furthermore, as highlighted by Elavarasan et al. (2018), these algorithms can assess environmental data—such as precipitation, temperature, and nutritional levels to predict potential dates and locations of disease outbreaks. This predictive capability can empower fishermen to prevent disease transmission and reduce the likelihood of incurring financial losses (Rajitha et al., 2007).

Numerous studies have explored the use of AI to analyse video footage from salmon farms, aiming to identify behavioral changes indicative of distress or stress. By employing deep learning algorithms, researchers successfully recognized patterns in the fish's behavior, allowing for the early detection of disease symptoms. Wu et al. (2022) highlighted four key areas of deep-sea aquaculture research: biomass estimation, water quality monitoring, intelligent feeding, and underwater inspection. The traditional manual methods have transitioned to mechanization and, ultimately, automation, leading to the development of unmanned intelligent equipment. The integration of these smart devices in various aquaculture applications can reduce labor costs, mitigate risks, and enhance productivity. In a closed recirculation system designed for denitrification, Lee et al. (2000) implemented a fuzzy logic-based control system. They developed a computer-controlled bioreactor for denitrification to facilitate squid research. Fuzzy logic was utilized to manage pumping rates and the addition of carbon feed to the

bioreactor by processing real-time data from sensors that measure dissolved oxygen, pH, and redox potential. Ultimately, the adoption of AI in detecting fish diseases has the potential to significantly enhance the health and welfare of fish populations raised in aquaculture.

3.3. AI application for biomass tracking

Biomass is a crucial factor influencing fish well-being and growth rates throughout their development stages (Li et al., 2020). The traditional method of estimating biomass involves sampling fish using a tray or fishing net, weighing each fish individually, and then calculating the total biomass (Martinez-de et al., 2003). This process can be labor-intensive and time-consuming, making it challenging to obtain a sufficient number of samples for accurate biomass estimation (Cai et al., 2020). Furthermore, this approach often leads to a high level of measurement inaccuracies due to human error. The fish may suffer from stress, nerve damage, or even mortality as a result of this handling. Additionally, the texture and quality of the final product can be compromised by the manual handling of deceased fish during post-processing for biomass measurement (Zion, 2012). Consequently, extensive research has been conducted to explore alternative methods for quantifying biomass (Li et al., 2020). The integration of artificial intelligence (AI) into aquaculture offers exciting new possibilities. By combining AI with imaging technology, it becomes possible to more accurately estimate the size, weight, quantity, and other biological characteristics of fish.

According to Monkman et al. (2019) indicated that the potential of machine learning and computer vision in fisheries management and environmental monitoring is exemplified by their application in predicting fish weight. These technologies have emerged as highly effective tools across various industries. A significant focus of numerous studies and research endeavors has been the use of machine learning techniques to enhance the accuracy of fish weight estimation. One notable approach involves analyzing fish photographs with computer vision algorithms to extract relevant data for weight estimation. Bravata et al. (2020) highlight that convolutional neural networks (CNNs) are being employed to assess fish images and precisely predict their weight.

a. Size Estimation: An important metric for managing marine resources is the length of the fish harvested. Certain fisheries management organizations require fishing vessels to record the lengths of the fish they collect (Tseng et al., 2020). Typically, fish body length is measured using rulers and tape measures; however, these methods are labor-intensive, subjective, and time-consuming.

b. Determining Age: One of the primary techniques for fish age classification currently in use is the automatic interpretation of fish otolith images (Bermejo et al.,

2007). Artificial training is essential for age prediction based on otolith images and has been effectively applied to tasks such as object recognition and various forms of image analysis. Moen et al. (2018) employed deep artificial intelligence to automatically identify otolith images and utilized transfer learning to adapt ImageNet pre-trained parameters to the developed CNN model for determining fish age.

c. Determining Sex: In recent years, biological methods were traditionally employed to identify the sex of fish (Du et al., 2017; Yarmohammadi et al., 2017; Webb et al., 2019). These approaches often resulted in trauma to the fish and substantial identification errors. In contrast, the machine learning methodology for sex determination relies on the fish's relative morphological characteristics rather than its age or condition.

3.4. AI in fish feeding

According to Ogunlela and Adebayo (2016) reported that the cost of feeding fish accounts for 40–50% of the total operational expenses in aquaculture. Srivastava and Liu (2015) found that 60% of the feed delivered to aquariums breaks down into particles. These particles which do put into the water which in turn require oxygen for decomposition and outcome harmful elements like ammonia and nitrogen which in turn do inhibit fish growth. Also a large element of what it costs to run a farm goes into fish food and that is what in great deal determines the profitability of fish farms. We see that at present we are using Artificial Intelligence (AI) in the design of better feeding programs. By looking at variables such as water temp, dissolved oxygen levels and the make-up of the feed we are able to develop predictive models that put out the best feeding plans and amounts for certain fish species. This in turn improves feed use and reduces waste also which in turn also promotes fish growth and health. In aquaculture feeding management AI does play a great role in fish behavior, weight, and maturation. Shrimp_feed can assess shrimp biomass and determine how much feed to distribute based on the data it collects (Chen et al., 2022). Industry in aquaculture, noted by O'Donncha and Grant (2019), strives to improve the rate of growth, whilst reducing the rate of environmental degradation from aquaculture activities. Research by Føre et al. (2018) shows that AI in feeding optimization can reduce waste, have a minimal negative environmental impact, and substantially increase fish growth rates while minimizing organic load.

3.5. AI help in fish growth

The ideal temperature for fish growth varies according to the species being cultured. Fish farmers can improve the rate of growth and survival by keeping the temperature within an optimal range (Uddin et al., 2022). However, there are upper and lower temperature thresholds beyond which growth rate will be decreased (Sivri et al., 2007). The correlations among growth rate, aquaculture and artificial intelligence (AI) are profound. One such correlation is the monitoring of

growth rate which is vital in the process. Keeping in view the growth rate of aquatic organisms, AI can improve the conditions in which they are grown and enhance the production to its maximum potential.

Today, various high-tech instruments are used to perform stereoscopic measurements on fish and shrimp to determine their size, shape, and location, and to track their activity. As noted, sonar cameras are able to record videos, using sound echoes to create images, and are therefore useful in murky and dark conditions (Li et al., 2020). Water quality in cages and large tanks can be monitored in three dimensions using autonomous vehicles equipped with sensors, which, as (Edan et al., 2009) illustrates, can profile a data set vertically in a comprehensive manner. Moreover, analytical algorithms can be used to automate the process of developing models to forecast the increase in size of aquatic organisms (Hmoud Al-Adhaileh & Waselallah Alsaade, 2021). These models take into account various environmental factors, such as nutrient availability, oxygen levels, and water temperature, to accurately assess growth rates (Ansari et al., 2021). This capability can aid farmers in reducing waste and optimizing their production methods. A predictive model can also determine the appropriate feeding rate for a fish species based on its growth rate, water temperature, and other environmental conditions (Ghandar et al., 2021). According to Bell et al. (2022), farmers can enhance productivity by implementing preventive measures and using predictive models to identify early signs of diseases or stress in aquatic species through environmental monitoring. By gathering data on feeding behaviors and growth rates, AI algorithms could potentially create customized feeding programs that maximize growth while meeting the specific nutritional needs of each fish (Metcalf, 2019).

3.6. AI in fish reproduction

The reproductive mechanisms of various organisms, including humans, animals, and plants, exhibit considerable diversity. In fish species, successful spawning requires maintaining specific temperature ranges, as temperature significantly influences fish reproduction. The reproductive and fertilization processes in fish involve several key steps, such as brood stock management, fertilization, hatching, and incubation periods. All these steps are affected by temperature and other water quality parameters, which can be regulated effectively through artificial intelligence (AI). By enhancing the regulation of fish reproduction, feeding, and growth, AI can improve fish health and well-being while increasing productivity and profitability for fish farmers (Ubina and Cheng, 2022; Khan et al., 2018; Mustapha et al., 2021).

3.7. AI in fish genome

The fish genome provides valuable genetic information,

and artificial intelligence (AI) can transform examinations, making them faster and more accurate. It aids in the development of new and more precise genetic tools for sustainable aquaculture and fisheries management (Song et al., 2023). With the assistance of AI, large amounts of genetic data can be analysed accurately, minimizing errors and complexities. By learning from vast datasets to identify patterns and make predictions, AI algorithms can effectively detect genetic variants and enhance our understanding of specific gene functions. Furthermore, AI can contribute to fish population surveillance by analyzing genetic variation and identifying markers that can track fish migrations and shifts in populations. Additionally, AI may be utilized to create novel genetic tools, including gene editing technologies, which can improve fish welfare and efficiency (Rasal and Sundaray, 2020).

3.8. AI in Fish breeding

Artificial intelligence (AI) can be utilized to develop predictive models of fish performance using genetic data, which can lead to more efficient and targeted breeding programs aimed at enhancing traits such as growth rate and disease resistance. By analyzing vast amounts of genomic data, AI systems can identify genetic variations associated with specific traits. This information can then be used to create models that predict fish performance (Dixit et al., 2023). These models can effectively forecast the performance of various fish populations under different environmental conditions and identify the best breeding candidates to achieve specific objectives, such as disease resistance or growth rates. The integration of AI in breeding operations may enhance efficiency and focus, ultimately reducing costs and saving time while producing desired traits. Increases in fish community sustainability and productivity can have a substantial positive impact on aquaculture and fisheries management (Mandal and Ghosh, 2023). Therefore, there is considerable interest in enhancing fish population genomic quality and growth performance, as well as in advancing aquaculture and fisheries management through the combined use of AI and breeding programs.

4. Challenges for AI in Aquaculture

Several restrictions and challenges that may impede the widespread adoption of AI in aquaculture. Not at all present are issues of safety which relate to our various tiers of integrated systems and networks. We see a great need to take complex data collection and turn it into simple representations of physiological relationships and diversity in different production systems. We have a issue with the lack of universal data formats and standards which in turn complicate data sharing between aquaculture farms and research institutions which in turn limits the use of AI in the field and also puts a crimp in the collection and analysis of large data sets. Into aquaculture we see

that a wide range of skills is required for the development and implementation of AI systems which includes data analysis, software development, and in depth knowledge of aquaculture practices. To fill in these skill and knowledge gaps we may have to put in place targeted training and education programs. Furthermore, the creation of advanced AI techniques and algorithms that can accommodate the intricate and adaptive nature of aquaculture operations presents an additional challenge.

5. Conclusion

Artificial Intelligence has the potential to transform the aquaculture sector by enhancing efficiency and providing continuous monitoring of fish development, nutrition, and breeding. It improves data analysis accuracy and aids in the planning and management of aquaculture farms. Furthermore, AI helps minimize losses caused by adverse ecological conditions and disease outbreaks within these farms. By enabling responsible and productive fish cultivation, AI contributes to ensuring a reliable supply of high-quality seafood to meet the demands of the growing global population. Adopt AI-based monitoring and decision-support systems in aquaculture farms. Provide training to farmers and professionals on AI and digital tools. Develop affordable AI technologies for small- and medium-scale farmers. Use AI for early disease detection and risk management. Encourage government support and public-private partnerships. Promote data sharing and standardized data systems. Focus on sustainable and eco-friendly aquaculture practices using AI.

6. Statements and Declarations

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Conflict of Interest: The authors have no potential conflict of interest to disclose.

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