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AI-Driven Aquafarming: Recent Innovations and Challenges to Enhance Sustainable Seafood Practices

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Abstract

Global seafood demand is increasing at a persistent rate to overcome food security issues. Traditional aquaculture methods are not enough to meet these increasing requirements. Therefore, new technologies using artificial intelligence have been introduced in small and large aqua farms. These technologies include IoT, 2D and 3D image detection, machine learning, robotics and computational technologies to overcome severe challenges faced by aqua farms. There are many challenges in the application of such AI techniques in aqua farms including, risks of data leakage, less reliability of stakeholders on AI methods, economic losses, knowledge and training gaps, incomplete information, ethical considerations and large amounts of data received which is again reviewed by peers, which then leads to a reduction in sustainable production. Integration of AI techniques with manual work helps in obtaining better production, enhancing fish growth and breeding, as well as careful monitoring of a complete ecosystem. From a future perspective, AI techniques play an important role in fish behavior analysis, early disease detection, genome sequencing, genome editing, efficient data-based decision making and fish species conservation which then leads to a more sustainable and efficient aquafarm. The involvement of stakeholders in careful monitoring of farming systems, government support and diverse aquaculture practices enhance farm production many times.

Keywords: Aquaculture; Aquafarming; Fish

Abbreviations

AI: Artificial Intelligence and IoT: Internet of Things.

Introduction

Aquafarming or aquaculture is an emerging trend that involves farming fishes, mollusks, crustaceans and other freshwater and marine aquatic organisms as well as plants under controlled conditions to reduce wild fish harvesting at a commercial scale [1]. Aquaculture is increasing globally at a vast rate and according to an estimation, sixty percent or two-thirds of the global fish production will be obtained from it by sinha [2].

Aquaculture plays a vital role in enhancing food security, increasing nutritional standards and decreasing poverty in underdeveloped countries. Asia's contribution towards aquaculture is the highest (89%) among all the continents [3]. Aquafarming is growing rapidly among other food production sectors. More than five hundred species of crustaceans, finfish, mollusks, seaweeds and other aquatic animals are being cultured globally [4].

It is difficult to manage and evaluate fish species by direct observation, as they live underwater. Traditional methods for observing aquafarm issues are not sufficient for completely assessing the status of a population and solving the problems regarding modern aquafarming [5]. As the fastest-growing sector for proper food supply worldwide, aquafarming is criticized because of its sustainability and effects on environmental stability [6]. Thus, to solve all these issues in large-scale fish culture, proper management of environmental problems and daily monitoring of fish stock is necessary, for which several aquafarming techniques have been used.

The most emerging technique for aquafarm monitoring is the use of Artificial Intelligence. It refers to the advancements and utilization of computer systems that are capable of learning, making decisions and solving problems, which are typically associated with human intelligence [7]. This integration of AI allows for more precise monitoring and management of aquafarming environments [8]. The most commonly used artificial intelligence applications in aquafarming are IoT (Internet of Things) [9], image identification [10], robot systems [11], processing natural languages and expert systems [12,13].

Artificial intelligence techniques monitor and control water quality, feeding strategies and early detection of disease which do not require much labor and cost, thus by using limited resources efficient results are obtained, which help fish farmers perform large-scale operations [14]. The AI algorithms improve the decision-making in aquafarming by assessing complex datasets, feeding schedule optimization and managing water quality and other factors affecting fish growth and health by using satellites, remote sensors and fish life histories [15]. Assessment of environmental conditions, fish physiology and behavioral patterns and early disease signs by using AI, fish farmers can reduce the spread of diseases and economic losses [16]. Genomic analysis by AI-driven models helps fish breeders develop their desired traits in fish to maximize fish growth and performance [17].

Although there are a lot of benefits regarding the use of AI techniques in aquafarming, several challenges remain, including the improper availability of data, AI model interoperability, ethical considerations and the usage of integrated AI methods over trusted traditional ones [18]. Overall, the integration of artificial intelligence enhances food security and supports sustainable practices. These advanced technologies require informed consent, data protection and ethical use to enhance farm production Thus, to solve such problems for the successful implementation of AI applications, collaboration among industry stakeholders and researchers, government support and regulatory bodies is required [19].

The Growing Demand for Seafood: Challenges Facing the Aquafarming Industry

As the world population increases, seafood demands increase and to overcome food scarcity issues, aquafarming is contributing a lot. Traditional methods of aquafarming are not very reliable and lead to problems like disease, aquatic pollution, overexploitation and degradation, reduction in profit percentage, economic losses and less information about market risks of aqua-farmed fish species [20]. There is a dire need for proper planning to resolve social, health, environmental and economic issues regarding important cultured fishes at all levels from local to international [21]. To overcome these challenges, Artificial intelligence is playing an important role in aquafarming as new techniques are introduced for sustainable development.

Role of Artificial Intelligence in Aquafarming; Innovative Technologies of AI in Aquafarming

Smart aquafarming is often referred to as the green revolution which combines modern information like artificial intelligence big data, the internet of things, camera videos and machine vision with fisheries for generating high yields and quality production. AI techniques, such as machine learning, genetic algorithms, and deep learning, have been employed to develop models that upgrade feeding strategies, identify optimal environmental conditions, and predict growth orientations by assessing the growth history of the farmed fish [22].

Smart Sensors and IoT Integration: Real-Time Monitoring for Optimal Conditions: Smart aquaculture model based on IoT (Internet of Things) measures all parameters of water quality (level of water, turbidity, temperature, pH and fish movements) for reducing cost and labor in aquafarms. Water is recycled to prevent diseases. Wireless sensors of short-range and small cost are utilized for proper monitoring of water, which provides error-free data as well as ensures fish growth and survival.

Real-time monitoring of fish ponds is possible by combining internet technology and sensors with user-friendly mobile, desktop and web service applications and thus decreasing loss risks and increasing fish productivity. Additionally, a GSM modem is also utilized for reducing internet usage, because on a farm internet availability is the major issue. Whenever the former opens their web or android application, interned is utilized, otherwise when parameters surpass the threshold limit, the GSM modem sends messages. The Internet of Things like controlling systems, mobiles, sensors, telecommunication and solar systems helps in achieving maximum and quality production [23].

Advanced Machine Learning for Disease Prediction: Traditional methods of fish farming involve several issues such as temperature fluctuations, water quality degradation, improper feeding and cost problems, which hinder aquafarming developments. For advanced monitoring, disease detection and prevention, observing aquafarming dimensions, behavior analysis, species identification, quality classification and sustainable production, machine learning techniques are introduced, which involve support vector machines and neural networks for analyzing water quality parameters and pond performance in aquafarming [24]. For enhancing production levels, decreasing breeding expenses and introducing intelligent aquafarming feeding methods, machine vision is used effectively [25].

Computer Vision for Behavioral Analysis: Computer vision technologies help detect fish, count and analyze their behavior, highlighting its role in improving quality and increasing aquafarming productions. Many challenges like low contrast, fish deformation, variation in illumination, high noise, dynamic background and continuous occlusions are faced by such computer-based technologies. The CVT has several unique fish detection applications, which are based on deep learning, fish motion and appearance, such as 2D and 3D image procurement by digital cameras, which have replaced the human brain and eyes for proper observation and discernment. These technologies aim to motivate researchers to create advanced algorithms for real-time decision-making and problem-solving that improve fish welfare, aquaculture productivity and quality while promoting sustainability [26].

Fish behavior is extremely susceptible to stress factors including environmental changes and high stocking densities [27]. A variety of methods have been introduced to observe and analyze fish behavior. One of the most common methods is video recording for proper observation in less time and does not require human presence [28], but long-duration videos which are again observed by a person make it a less valuable tool. Motion analysis and automated image analysis of fish are some other emerging techniques used for assessing fish behavior [29], enabling precise tracking and assessment of fish individuals [30]. Despite advancements, no system currently exists to track particular behavioral aspects like fish's ability to escape [31].

Image detection of fish freshness: a case study: Fish quality and freshness are influenced by various factors during its production, food preparation, transportation and sale. Fresh fish is highly preferred because it's a nutritional food source with having high content of proteins, vitamins and omega-3 fatty acids, but consumers often face problems in assessing its freshness. Traditional methods such as tactile evaluation of fish can cause contamination and foodborne illness [32,33]. For properly maintaining fish quality, controlled temperature conditions are required from harvesting to consumption. For assessing the freshness of seafood and solving other related issues, new technologies like Hyperspectral imaging and Rapid protein liquid chromatography techniques are introduced. These are based on the physical, microbiological, sensory and chemical properties of fish [34].

For the classification of fish based on their freshness, a study has been introduced, known as deep learning algorithms (SqueezeNet and Inception V3) which uses a dataset containing fish body 4476 images, which gives out information that either fish is stale or fresh. The findings revealed that a 100% accuracy rate is obtained for every deep learning method using ANN, SVM and LR models. Compared to the previous study, where this percentage was 98.0, this result shows a higher proportion [35].

Robotics and Automation: Transforming Operational Efficiency: Aquafarming is the fastest-growing industry for food production in the last decades and provides innovative solutions for reducing risks and costs and enhancing sustainable systems and productions. To perform a variety of tasks, robotic system utilization has been promoted in aquafarming in the past few decades because of its ethical and social benefits as well as accuracy in performing high-risk tasks. Automation in aquafarming will enhance human control through autonomous underwater robots, which will improve future research and innovations in precision fish farming, aiming to digitize and industrialize farming operations [36].

In order to prevent inefficiencies, high costs and labor in aquafarms, where monitoring and handling of fish is performed by multiple workers, the standard system of aquaculture known as the Internet of Things (IoT) is introduced which merges cloud and IoT technologies. Autonomous systems powered by advanced sensors, Artificial intelligence and big data will enhance future productions and reduce costs [37]. Robots and Intelligent machinery can control large amounts of data powered by intelligent fish farms because AI gives them intelligent brains, that can learn, judge and make decisions just like humans [38].

Robots and other intelligent machinery use machine vision, navigation, computing and precision control technologies to replace labor with machines. The advanced tools use modern information and manufacturing technologies to execute precise operations in intelligent fish farms [39]. The intelligent fish farm equipment includes mobile equipment such as unmanned ground and aerial vehicles, unmanned ships and surface vessels as well as unoccupied underwater robots. For proper monitoring of oxygen, feeding and water quality, fixed equipment is used [40].

The Multifaceted Benefits of Artificial Intelligence in Aquafarming

Artificial intelligence (AI) has revolutionized aquafarming by increasing production efficiency, promoting sustainability and reducing labor intensity in fisheries to prevent extinction. It helps in monitoring fish activities, combat illegal, unreported and unregulated fishing and minimizes input waste, thus increasing cost savings by up to 30%. By using AI technology, aquafarming can address challenges like environmental degradation, overexploitation and resource limitation, while satisfying the growing requirements of seafood worldwide [41].

Maximizing Resource Utilization and Operational Efficiency: Aquafarming is severely impacted by environmental issues, workforce reliance, competition for water sources and disease outbreaks which can decrease the productivity, resilience and sustainability of farmed fish and systems. The above-mentioned technologies using AI can transform the aquaculture industry into a more sustainable and reliable industry by maximizing resource utilization like proper water management. By using these technologies operational efficiency is maximized which provides properly managed, environment-friendly and less workforce-dependent aquafarms which will then reduce problems regarding food security all over the globe. The active involvement of all stakeholders is necessary for harnessing the benefits of automation and sensing innovations in aquafarming [42]. For a sustainable aquafarm, AI helps optimize fish health, growth and proper feeding. The environment is properly monitored, such as water quality parameters are analyzed regularly by using AI techniques which improves fish health.

Empowering Data-Driven Decision-Making and Supporting Biodiversity: Aquafarming is experiencing a data-driven innovation revolution, driven by the rapid adoption of digital technologies that generate large datasets to increase decision-making for sustainable aquatic food systems. Besides knowledge about the efficiency of digital tools, their implementation is still difficult because the present ecosystem for utilizing such techniques is highly fragmented. The main focus is on private farm-level data for enhancing efficient farm production and little public knowledge is available for maintaining social and environmentally stable systems. Ongoing fragmentation, centralization and collaboration within a fragmented ecosystem are some potential future scenarios for the future evolution of aquafarming data ecosystems, which is seen as most promising for fostering sustainability [43].

Biodiversity, water quality, usage of land and changing climatic conditions are all involved in environmental monitoring by artificial intelligence technologies. Instead of using costly, less reliable and time-consuming traditional methods, AI use has been promoted in aquafarms in recent decades because of its effective biodiversity management and conservation strategies [44]. In recent years, the latest innovations in aquafarming operations at the commercial level involved the usage of artificial intelligence techniques. Such techniques enhance fish, other aquatic organisms and aquatic plant production when cultivation is done under controlled conditions and provide solutions for enhancing decision-making quality to satisfy increasing demands of seafood at the global scale [45]. When decision-makers face problems like investment and policy decisions in making good decisions about precise aquafarming, decision-support systems help them but there is a lack of data about decision-support systems [46].

Enhancing Fish Health and Welfare Through Early Detection: Maintaining the sustained health of fish is very important for enhancing production on farms. In inland fish farming, small-scale fish farmers play an important role, who cultivate fish in pens and ponds where manual monitoring is done. There are several issues about manual observation of farmed fishes, such as less reliable data, high time lag and easy disease outbreaks due to low quality of water, which in turn decrease fish production and cause economic losses at a vast scale. To overcome such issues, AI technologies are introduced, which involve machine vision, the use of robotics and many other techniques.

The AI helps in optical monitoring and timely observation of any problem regarding fish, like disease outbreaks, so that timely prevention or treatment can be applied. As soon as some disease outbreak is detected, instant messages are sent to the shareholders to take remedial actions, which in turn increases farm efficiency, minimizes time lag and saves farms from economic losses [47]. Machine learning uses real-time data to check water quality parameters and detect diseases to help disease prevention in fish farms. A neural network-based classification system is utilized to train and classify the diseases because early detection enhances the chances of timely prevention and limiting economic losses [48].

Exploring the Role of AI in Sustainable Development and Environmental Monitoring: Environmental monitoring and sustainable development are increasing by using Artificial intelligence. Many environmental issues are controlled with the help of AI because of its abilities like automation, predictive modeling and proper data analysis, which provides more precise and efficient data. Artificial intelligence aids in real-time monitoring of pollution levels, ecosystem variations and climate patterns, which enables early actions and making well-informed decisions. More sustainable practices are also aided by AI-driven advancements in resource maximization, waste reduction and energy management in ecosystems. To achieve global environmental goals for environmental preservation, there is a dire need to use AI in all fields. It is a sustainable method for providing reliable solutions for environmental protection and management [49].

Challenges Faced by Artificial Intelligence in Aquafarming

Economic Barriers: There are many economic factors, that significantly hinder the use of AI in aquafarming, including initial investments, cost requirement for regular maintenance and the unwillingness of stakeholders in system investments due to which economic benefits are reduced [50]. Many farmers are unwilling to shift from traditional methods to artificial intelligence techniques because they think that by using such technologies benefits are negligible. Stakeholders are already risk averse, therefore to prevent investment loss and avoid risk, they do not prefer to use AI, as the time which is required to convert whole systems from traditional methods to AI-based aquafarms causes problems in their decision-making ability [51].

Knowledge and Training Gaps: Improper knowledge and lack of skills in stakeholders for developing reliable systems is also one of the biggest challenges faced by AI techniques. Proper knowledge about software and hardware usage is necessary for productive farming, but due to the complexity of these techniques, many stakeholders and laborers feel overwhelmed [52]. Due to insufficient knowledge and training about using AI techniques, production is not enhanced and resources are not properly utilized. Training requirements for using AI techniques are difficult, because of information overload, which also discourages stakeholders from adopting these techniques in the placement of traditional methods [53].

Information Deficiencies and improper datasets: The algorithms of AI mainly focus on the availability and quality of data, which is difficult in aquafarming, especially where farms are developed in offshore areas. Proper resources are required for collecting large data sets, which is a very time and cost-consuming process. Therefore, a significant challenge in the adoption of AI techniques is also the lack of organized information, perceived risks, incomplete availability of good-quality data, unclear procurement methods and technology benefits. Improper information about the functioning of the latest technologies and their benefits, decreases stakeholders' reliance on using them, ultimately leading to a reduction in acceptance and adoption of such techniques [54,55].

Security Concerns and Ethical Considerations: Aquafarming is evolving to meet the global food requirements, but due to data sensitivity values in comparison with other fields like healthcare, a concern occurs about data security. Sensitive data collection and storage about fish health, market intelligence and farm practices raise security concerns alternatively leading to raised ethical considerations [56]. There is a chance for operational data disclosure, therefore stakeholders authorize decision-making systems. Although AI replaces machines over humans, the output data is still handled by manufacturers, which itself is a complicated process, leading to complicated decision-making for adopting such techniques [57,58].

Cost and Infrastructure Limitations: Artificial intelligence technologies require high costs for appliances, sensors, systems for data collection, computational resources and highly skilled workers, which means a complete infrastructure is required for an efficient intelligent aquafarm. There is a lack of energy sources and telecommunication networks in small farms and rural areas, which hinders the proper utilization of AI techniques. To adopt such techniques, a continuous power supply, good quality internet and technical support are required, in the absence of which, AI techniques do not work properly, thus discouraging stakeholders from shifting their farms from traditional methods to AI systems [59].

Issues with Interoperability, Usability, and Mindset: Interoperability issues, stakeholders' mindset and user experience challenges are the factors that prevent the adoption of AI in aquafarms. Traditional systems and new AI techniques should be compatible because the stakeholders rely on numerous manufacturing products made by the integration of both methods. Most fish farmers are hesitant to use AI techniques without the opportunity for testing, therefore user-friendliness of these techniques plays an important role [60,61]. Lack of reliance on using AI techniques as an alternative to traditional methods also hinders their adoption applications [62]. Other issues such as lacking peer testimonials and complex deep-learning models which are necessary for decision-making in aquafarming also hinder AI applications leading to decreased stakeholders' reliance. Transparent AI technologies enhance fish growth and welfare, as well as build the trust of stakeholders, but such issues block this transparency [63].

A brief Solution to Challenges Faced by Aquafarms

Problem-solving for the successful application of AI, collaboration among industry stakeholders, researchers and regulatory bodies is required. Overall, the integration of artificial intelligence enhances food security and supports sustainable practices. These advanced technologies require informed consent, data protection and ethical use to enhance farm production.

Research and Development: Fostering Collaborative Innovations and Future Perspectives

Artificial intelligence is an important technology for developing intelligent decision-making systems and upgrading traditional aquafarms into more sustainable ones.

Enhancing Aquafarming Efficiency: The Role of AI in Optimizing Fish Feeding, Sustainable fish feeding is an important part of aquafarming because 40-50% of total aquafarming operational cost is feeding cost, while the remaining 60 % is wasted and causes water pollution [64]. For sustainable production, the integration of fish appetite and feed dispensation should be used. Fish feeding can be optimized by using AI for the calculation of serving sizes and ideal schedules and developing predictive models based on factors like dissolved oxygen, water temperature and nutritional content to evaluate suitable feeding amounts and times, thus improving feeding and reducing waste [65]. Sensors based on AI are used to detect fish hunger and behavioral patterns, thus feeding strategies can be adjusted according to the situation. By keeping genetic variables like body, weight and age as a base, feeding plans can be created, which leads to a precise aquafarming approach that maximizes growth and minimizes environmental issues [66,67].

Artificial Intelligence Utilization for Observing Fish Behavior, Sustainability and Efficiency

Water quality and waste levels are important environmental factors that are monitored in aquafarms for sustainable production and risk reduction related to disease outbreaks, thus supporting aquafarms for sustainable food supply. Fish behavioral analysis, such as aggression levels is also important to consider. Temperature management is also necessary because at high temperatures fish (e.g. largemouth and tilapia) become aggressive, while at low temperatures metabolic activity of fish decreases [68,69]. Artificial intelligence is used by technological solutions, like Umitron systems, to optimize feeding times and monitor swimming behavior, resulting in a considerable reduction in waste and enhancement of feeding efficiencies. Artificial intelligence helps in understanding and management of fish behavior which then guides the producers to grow healthier fish having high growth ability [70].

AI-Driven Temperature Management in Fish Growth and Reproduction

Maintenance of ideal temperature conditions is essential for promoting the growth of fish but fluctuations in temperature reduce it [71]. Temperature has a significant impact on the successful spawning of fish, therefore by adjusting controlled temperature conditions, fish production is elevated. Artificial intelligence using advanced techniques like sonar cameras and stereoscopic observations by evaluating the shape, size, growth and behavior of fish, helps in the enhancement of water quality, feeding and disease prevention [72,73].

Fish health, productivity and profitability have all been improved by using AI techniques which help in the formation of customized feeding plans for salmon and developing predictive models for identifying ideal reproduction conditions, such as striped bass egg production [74]. These techniques use genomic data to develop predictive models for improving fish breeding plans, better fish performance, disease resistance and increasing growth rates, which in turn improves the productivity and sustainability of global fisheries.

Genetic Conservation of Endangered Fish Species Through AI

For the conservation of endangered fish species, assessment of genetic diversity, as well as identification of distinct populations is done by using genomic data, which is then properly analyzed by using AI techniques or algorithms. This information helps in developing healthy aquatic ecosystems and reducing anthropogenic risks of habitat loss and overexploitation [75]. Artificial intelligence focuses on traits like disease resistance to help in genetic variability tracking and making conservation efforts for threatened species, thus developing a healthy and sustainable ecosystem and maintaining biodiversity [76].

Fish Genome Sequencing and Editing by using AI

Artificial intelligence is revolutionizing the research based on fish genomes by accurately assessing fish genomic data. New genetic tools have been developed in aquafarming and fisheries management by using AI techniques [77,78]. The utilization of AI helps in the careful monitoring of fish populations and enhances breeding practices by identifying diverse genetic patterns [79].

It also increases genome sequencing and integration methods. The AI technologies increase speed and accuracy for determining fish species' genetic makeup and required traits, which then helps the fish farmers select optimal breeding candidates [80]. Fish growth and disease resistance abilities are enhanced by using AI-refined technologies for genome editing like CRISPR-Cas9 [81]. The AI predicts efficient targets of genome editing and reduces off-target effects [82]. The integration of AI with genome analysis and editing plays an important role in significant aquafarming production [83].

Future Perspectives for Aquafarm Sustainability

Collaborative Research Initiatives: Connecting Academics and Industry: Accelerating the development of AI techniques to develop an innovative and sustainable aquafarm, requires a collaboration between industry stakeholders and academic researchers. Their collaboration will accelerate farm production to meet increasing global needs.

Policy Frameworks: Encouraging Sustainable Practices: Proper policy frameworks are essential to promote the sustainable use of artificial intelligence in small and large-scale aquafarms. For the adoption of AI techniques in a controlled manner, the government plays an important role by providing proper guidelines and funds to stakeholders. With the help of government, AI techniques can be upgraded for more sustainable production of aquafarms.

Global Perspectives: Learning from Diverse Aquafarming Practices: Aquaculture conditions vary from country to country, but for adopting AI techniques, a global perspective should be considered. Using AI integration management systems, sharing best practices and lessons learned can enhance the sustainability of diverse ecosystems and fulfill increasing seafood supply for future generations.

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