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ORIGINAL

Artificial Intelligence-Driven Smart Aquaculture: Revolutionizing Sustainability through Automation and Machine Learning

Acuicultura inteligente impulsada por la inteligencia artificial: revolucionando la sostenibilidad a través de la automatización y el aprendizaje automático

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ABSTRACT

AI incorporation in aquaculture has transformed the industry completely, making crucial processes automated, maximizing productivity, and promoting sustainability. AI, specifically machine learning, refers to the application of modern smart aquaculture systems for tasks such as fish species classification, health monitoring, feed regulation, and management of water quality. It thereby sets inefficiency issues right while reducing impacts on the environment through real-time data-driven decision-making. This article deals with very recent developments in the applications of AI and machine learning in aquaculture, pointing out their importance in increasing production as well as eco-friendly management of aquatic environments.

Keywords: Artificial Intelligence; Machine Learning; Smart Aquaculture; Automation; Fish Health Monitoring; Sustainable Production; Water Quality Management.

RESUMEN

La incorporación de la inteligencia artificial (IA) en la acuicultura ha transformado por completo el sector, automatizando procesos cruciales, maximizando la productividad y promoviendo la sostenibilidad. La IA, concretamente el aprendizaje automático, se refiere a la aplicación de modernos sistemas acuícolas inteligentes para tareas como la clasificación de especies de peces, la supervisión de la salud, la regulación de la alimentación y la gestión de la calidad del agua. De este modo, corrige los problemas de ineficiencia y reduce el impacto sobre el medio ambiente mediante la toma de decisiones basada en datos en tiempo real. Este artículo trata sobre los avances más recientes en las aplicaciones de la IA y el aprendizaje automático en la acuicultura, señalando su importancia para aumentar la producción y la gestión ecológica de los entornos acuáticos.

Palabras clave: Inteligencia Artificial; Aprendizaje Automático; Acuicultura Inteligente; Automatización; Control de la Salud de los Peces; Producción Sostenible; Gestión de la Calidad del Agua.

INTRODUCTION

Background and Relevance

Over the last two decades, global aquaculture has grown dynamically due to the increased demand for species such as carps, catfish, tilapia, bivalves, and crustaceans. These species dominate the global production stock and are raised in quite varied environments, such as freshwater, brackish, or marine aquaculture. However, the chief challenges for the industry are impacts on the environment and production efficiency that is relatively low. The most traditional sources of aquaculture mainly rely on labour-intensive processes in relation to seed selection, feeding, and water quality monitoring.[1] The processes are very inefficient and time-consuming.

Importance of AI and Automation in Aquaculture

The present situation is forcing the aquaculture industry to shift towards smart systems to address inefficiencies and reduced environmental impact. Integrations of innovative technologies like IoT, big data, AI, 5G, and robotics would make smart aquaculture technology mechanize and optimize necessary activities associated with real-time surveillance of the aquatic environment for the purpose of data-driven decision-making.[2]as well as artificial intelligence (AI Thus, automatic roles for fish and other aquatic species mainly lead to cost savings on labour, accuracy, and timely intervention to ensure optimal conditions. Such technologies, for example, AI and IoT, are already being applied in tasks like water quality monitoring, automatic feeding, and fish behaviour analysis, and transforming aquaculture into an efficient and productive industry.

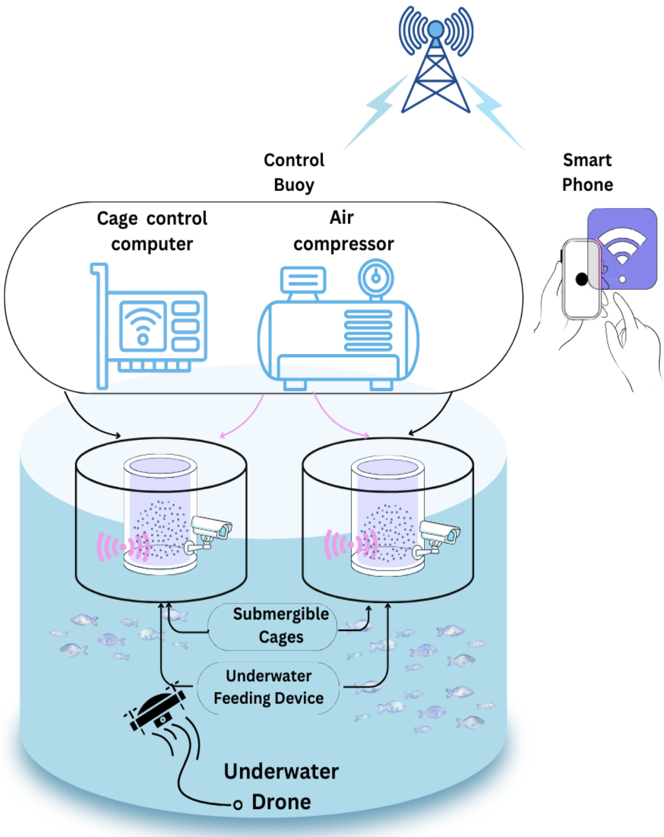

Figure 1. Conceptual Model of Automated Aquaculture System

Impact of AI and Machine Learning on Aquaculture

AI, machine learning in particular, is at the core of the change described below, bringing a revolution to aquaculture management. These models include decision trees, Naive Bayes, support vector machines, neural networks, and deep learning - all able to learn from experience and be updated over time.[3] These models can be adapted for various tasks, including biomass estimation, counting fish, identifying species, and examining the health status and the feeding patterns of fish.[4] Utilizing AI and ML, farmers can optimize production while keeping aquatic species healthy and sustainable in the best possible ways through better management decisions. This outline will help one structure the introduction in a clear and concise way, especially by underlining how AI and automation can really transform the aquaculture industry.

Literature Review

Smart Aquaculture

Smart aquaculture employs new technologies that can optimize the management of aquaculture. It involves all aspects of fish farming, from breeding and nursery through grow out, for increased production and yield.[5]

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This new generation of techniques also encompasses issues that conventional methods did not cover, such as the management of water resources, feed optimization, and automating feeding processes. In smart aquaculture, tasks such as fish classification, counting, and cleaning are conducted, just like earlier times when the fishermen have to do this manually. The smart system significantly enhances the ability to manage production as well as to support environmental sustainability in aquaculture operations.[6] Thus, it has significant potential for use globally in meeting food production with minor effects on the environment.

Smart System Monitoring of Aquaculture Water Quality

Water quality is one of the most vital factors governing the success of aquaculture. Some of the significant parameters that include temperature, turbidity, carbon dioxide, pH, ammonia, and nitrates must be monitored to ensure healthy conditions for the fish.[7] Of these, temperature, dissolved oxygen, and pH levels are the most critical indicators of fish health and growth. Over the past few years, the Internet of Things has emerged as one of the biggest changes that has been introduced in the field of real-time monitoring and management of water quality in aquaculture systems.[8] IoT has provided farmers with the benefits of attaining accurate, real-time measurements of the various parameters in water using sensors, which in turn leads to better management of the aquaculture environment. Normally, an IoT-based aquaculture system consists of four layers: the Physical Layer (sensors), the Monitoring Layer (data collection), the Virtual Layer (data processing), and the Connection Protocol (communication between devices). These systems provide farmers instant feedback, which they can use to make timely decisions for keeping water at ideal quality. Even with diseases in fish, it is likely to be detected at an early stage through IoT, thus avoiding important losses in production. Fully automated aquaculture systems are not yet achieved because of the distinctive features of the industry; however, many practices in water quality monitoring begin to be increasingly automated. There are many studies on IoT integration in aquaculture as well as integrating AI for improved water quality monitoring. For instance, with water parameters such as temperature, dissolved oxygen, pH, and ammonia levels using the Raspberry Pi and sensors, farmers can monitor water quality in real-time, and the data gathered from these sensors can be saved on cloud servers that can be accessed via mobile applications to monitor and control. Another application used IoT-based RAS, where it used the MQTT protocol for communication and real-time monitoring of water quality.[9]

Other systems come fitted with the addition of features such as temperature, light intensity, and water level sensors sending notification to farmers via apps in case there is a problem. With more than one sensor connected to the microcontrollers like Arduino Uno, complex systems will further display real-time data on cloud platforms. IoT systems use sensors to measure temperature, pH, and turbidity in lakes or ponds to monitor water quality. The data is sent in real-time to mobile devices for easy monitoring.[10] With IoT systems, parameters like temperature, salinity, pH, and dissolved oxygen can be continuously monitored and optimized to achieve ideal fish rearing conditions.[11] The data can also be stored in the cloud for better predictive and analytical abilities using machine learning models. Thus, machine learning algorithms turn aquaculture into a much more precise and efficient water quality management system.

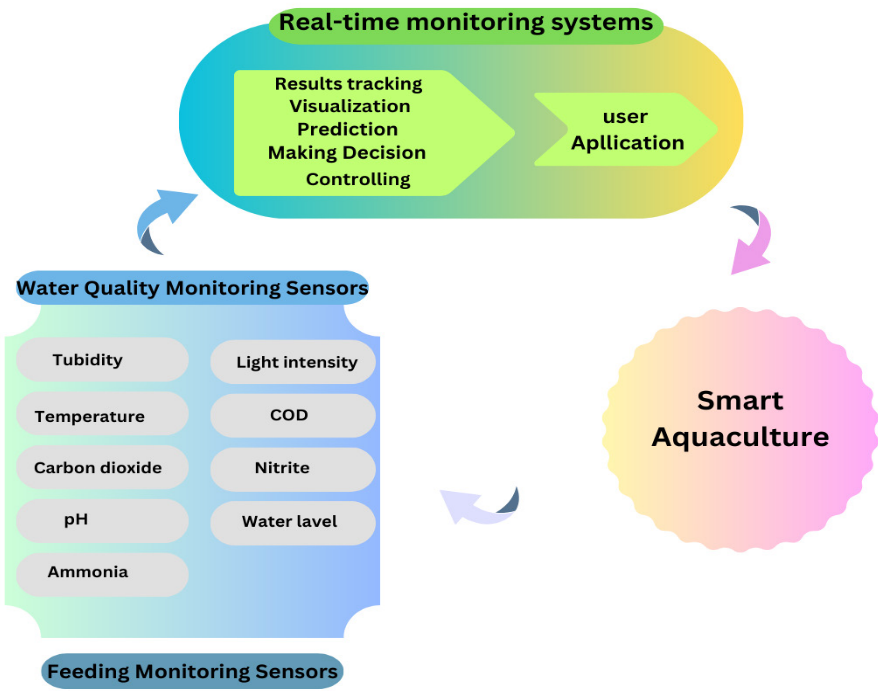

Figure 2. Smart Aquaculture: Sensors and Monitoring Infrastructure

Feeding Control

Feeding is one of the management aspects that are critical in aquaculture. Traditional feeding systems are, however usually inefficient and wasteful. Feeding in the traditional system is usually done by throwing food into the ponds or feeding at fixed points as the fish feed. Such a system usually results in huge feed wastage, pollution of water, and inefficient labour. These are the challenges that are gradually bringing demand for IoT enabled feeding systems that have the ability to automatically monitor and control the amount of feed dispensed so that the fish can get feed for the correct amount at the correct time. Several researches were focused towards the development of the automated feeding systems that include IoT. The semi-automatic system that detects water quality and controls feeding as well.(12) The system employs sensors like pH and temperature sensors, with an Arduino Uno board and a DS18B20 temperature sensor and a SIM900A GSM module. The GSM sends notifications to the farmer when water quality parameters have exceeded normal values while the system automatically dispenses food according to the needs of the fish. In this respect, it significantly reduces labour costs, prevents feed wastage, and maintains optimal conditions within the aquaculture environment. Daud et al. An IoT system for smart aquariums has been proposed, using Arduino MEGA and Node MCU microcontrollers to allow farmers to monitor and control water parameters and feeding via a smartphone.(13) The system provides real-time information with an LCD and the Node MCU Wi-Fi module gives remote access to the data. This is convenient to farmers and ensures that both water quality and feeding conditions are managed consistently. An IoT-based water quality monitoring system for fish ponds is designed to monitor parameters like temperature, pH, and dissolved oxygen while synchronizing with feeding schedules to feed accordingly. All the computed data collected are stored in the cloud, through which farmers can easily access information for real-time monitoring. Such systems aim to optimize aquaculture operations, like automating feed intake and water quality management in reducing feed wastage and pollution and increasing overall health and productivity in fish farms. Such systems are integrated with technologies like Arduino microcontrollers, DS18B20 temperature sensors, pH sensors, and GSM modules, and all of them focus on improving the efficiency and sustainability of resources in efforts to improve feeding practices and manage water quality.(14)

Machine Learning in Aquaculture

Machine learning is one of the most comprehensive applications of AI. It allows systems to learn without being explicitly programmed. Instead of having a piece of code that states what to do, ML models are actually trained to find the best patterns from the data and then create decisions from there. Such an approach will greatly enhance the accuracy and efficiency of different tasks within aquaculture, especially in monitoring and predicting as well as automatic control of systems. Classification of ML methods is normally done as supervised, unsupervised, semi-supervised, and reinforcement learning methods. Each category has different features and is suited for application in various aspects of aquaculture. The best-known form of machine learning is called supervised learning. This is training models on labelled datasets, meaning the input data are presented with the right output. This would facilitate the model to "learn" and predict new, unseen data accurately. In aquaculture, for instance, supervised learning can be used to identify some patterns in water quality, such as alterations that may negatively impact fish stock. On the other hand, unsupervised learning does not require labelled data. Instead of trying to identify the hidden underlying correct output, it views and clusters input data based on inherent similarities or patterns without knowing the right output. It may relate to a job like clustering the fish species by the body features or categorizing the behaviours in a school of fish.

Semi-supervised learning is a combination of supervised and unsupervised methods. This method uses very few labelled data along with many unlabelled data for the improvement of accuracy of a model that reduces the need for large amounts of labelled datasets. Its application may be particularly effective in cases where acquisition of labelled data is expensive or extremely time-consuming, as is commonly observed in large aquaculture systems. Finally, there is reinforcement learning. It involves the interaction of the learning system with its environment to receive feedback in the form of rewards or penalties. Such a feature is beneficial for complex aquaculture-related operations, like scheduling feeds according to the behaviour of the fish and prevailing environmental conditions. A few common machine learning models are applied in the aquaculture system. These include decision trees (DT), support vector machines (SVM), naive Bayes (NB), artificial neural networks (ANN), deep learning (DL), ensemble learning (EL), and k-nearest neighbours (KNN). While one of each model has diverse strengths and weaknesses, decision trees and SVM are very accurate but will fail on missing data. Models like naive Bayes and KNN are more robust and don't have as many issues with missing data. Because of its ability to handle complex and high dimensional data, deep learning-one type of ML-has been popularized, including using it to analyse images of fish or for real-time monitoring of environmental conditions.(15)

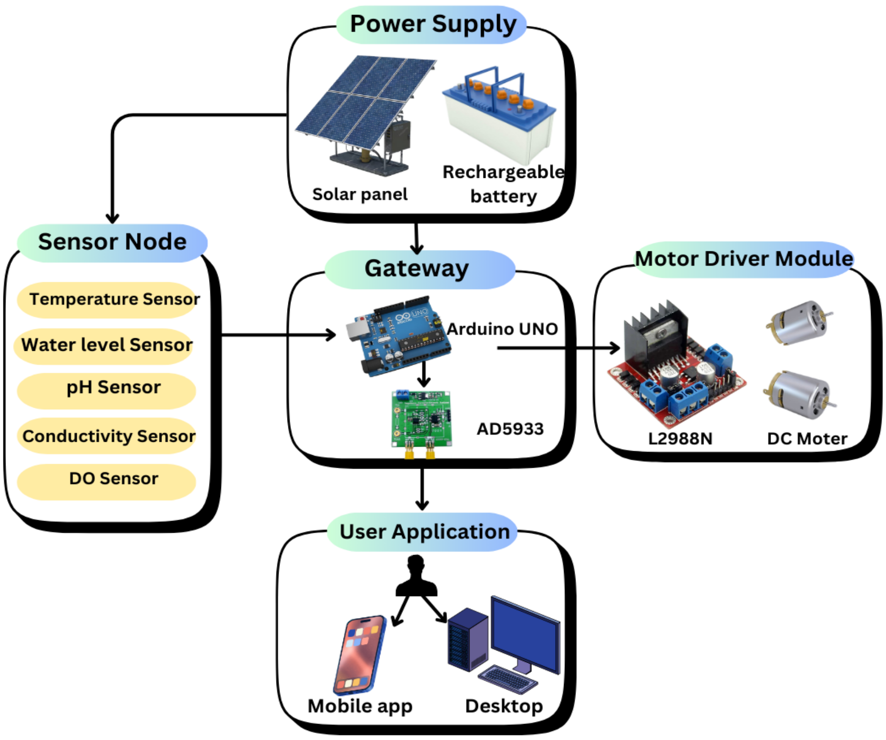

Figure 3. Block Diagram of IoT Water Quality Monitoring System

Integrating Machine Learning and Computer Vision in Aquaculture

Machine learning and computer vision are transforming aquaculture by automating labour-intensive tasks such as fish measurement, health monitoring, and feeding optimization. These technologies reduce human error and improve efficiency, enabling more accurate and scalable fish farming operations.

Automated Measurement and Classification Systems for Fish

The proper measurement of the length and weight of fish is essential in identifying growth, health, and best-readiness for market. The traditional methods of measurement are manual. This process is time-consuming and prone to errors. The application of machine learning and computer vision better provide non-invasive methodologies. Systems comprising cameras and image processing software can measure fish and identify species on-line in real-time with high accuracy and throughput. For example, the system developed for halibut and plaice species made 100 % accurate sizing of fish at rates up to 30 000 per hour using a conveyor belt and lightbox arrangement. Other scholars have developed analysis techniques for deformities or diseases in images and substantially improved the quality control of fish farming.

Aquaculture Intelligent Feeding System

In aquaculture, feeding is a primary process but also an energy-intensive process.

Aquaculture Intelligent Feeding System automatically conducts both overfeeding and underfeeding problems by optimizing feed distribution based on observed behaviours and data from fish environments. The system uses computer vision to monitor fish activity, which directly modifies feeding in response to this activity to improve health and growth rate and save feed resources. Some of the advanced systems incorporate water quality parameters, such as pH and temperature, with sensors and GSM modules that alert the farmer when conditions are outside the optimal ranges.[16]

Machine Learning Advancements in Aquaculture Health Management

By far, fish health is the most significant aspect in aquaculture because the sudden outbreak of disease can result in enormous losses. Machine learning and computer vision technologies enable early diagnosis of diseases based on changes in swimming behaviour, body shape, or other visual symptoms. Additional information on environmental sensor data, such as pH, temperature, and dissolved oxygen levels, could also be used to predict disease risk, thus providing ample opportunities for intervention well before mortality and reducing mortality rates.

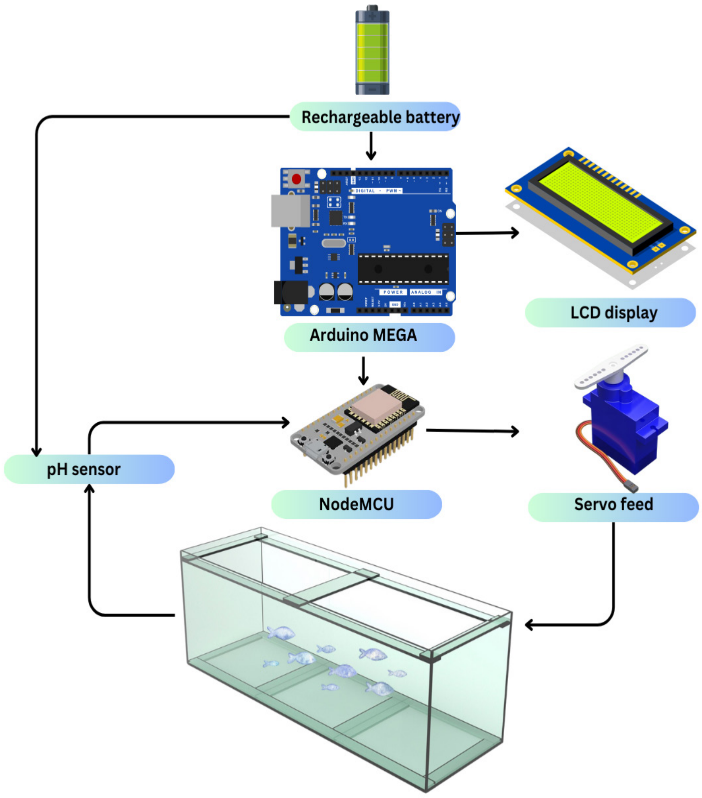

Figure 4. System Architecture for IoT Application

Vision-Based Health Monitoring and Weight Estimation

A machine vision system designed to weigh salmon accelerated the process and improved accuracy without placing much stress on the fish and labour demands on the workers. It captures images of the fish for a more efficient weight estimation than when it is done traditionally. Starting from feeding to health monitoring processes, aquaculture farms can improve productivity with minimal costs in the long run with the integration of machine learning and computer vision.

Future Developments of Machine Learning in Aquaculture

Automation and computer vision will indeed revolutionize aquaculture, despite high development costs. They are likely to become more accessible and cheaper and become ubiquitous in the industry, and fish farming will be conducted more efficiently, sustainably, and profitably.

The Recent Trends of Automation and Data-Driven Aquaculture

Aquaculture in the future will involve integrating more advanced algorithms of machine learning, including real-time data analysis. On the horizon are emerging trends that include precision aquaculture, whereby all aspects of fish farming from individual fish behaviour to overall ecosystem health are monitored and optimized through data-driven approaches. Innovations will significantly improve productivity, as well as decrease environmental impacts and welfare factors for the fish themselves.

CONCLUSION

In recent years, the acceptance of smart aquaculture practices, such as machine learning and computer vision, has significantly improved efficiency, automation, and accuracy in aquaculture systems. However, these technologies have yet to be fully implemented due to the complexity of fish farming processes and the involvement of human decision-making and management. Although these technologies have been developed, the cost of implementation remains high, making them more applicable to large industries and species with high economic value. Nevertheless, the accuracy and speed of machine learning and computer vision are much higher than current manual methods. This paper reviewed various applications of artificial intelligence, including machine learning and computer vision, for species identification, fish disease detection, feed regulation, and water quality monitoring. In the future, these technologies may be applied to offshore aquaculture systems for real-time monitoring of fish health, cage safety, and fish size measurement. Such systems would address current challenges in offshore cage farming, such as the inefficiency of manual observation and examination by divers.

Machine learning, combined with submerged cameras, could automate processes like fish disease detection, weight control, and cage safety management, leading to a more efficient and secure method of offshore fish farming.

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CONFLICT OF INTEREST

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