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Role of artificial intelligence (AI) in fish growth and health status monitoring: a review on sustainable aquaculture

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Abstract

Aquaculture plays a crucial role in meeting the growing global demand for seafood, but it faces challenges in terms of fish growth and health monitoring. The advancement of artificial intelligence (AI) techniques offers promising solutions for optimizing fish farming practices and ensuring sustainable aquaculture. This abstract provides an overview of the role of AI in fish growth and health status monitoring, emphasizing its significance in promoting a sustainable aquaculture industry. AI technologies, such as machine learning and computer vision, have shown immense potential in analyzing large volumes of data collected from fish farms. By leveraging AI algorithms, fish farmers can gain valuable insights into fish growth patterns, feeding behavior, and environmental factors affecting fish health. These algorithms can detect and predict anomalies, diseases, and stress indicators, enabling proactive interventions to mitigate health issues and reduce losses. One of the key applications of AI in aquaculture is the development of smart monitoring systems. These systems employ various sensors, cameras, and data analytics tools to continuously collect real-time data on water quality, temperature, oxygen levels, and fish behavior. AI algorithms analyze this data to identify deviations from optimal conditions and provide timely alerts to farmers, allowing them to take appropriate actions such as adjusting feeding schedules, modifying water parameters, or administering treatments as needed. Furthermore, AI-based models can assist in optimizing feed management and reducing wastage. By analyzing historical data on fish growth and feed consumption, machine learning algorithms can determine the most efficient feed formulation and feeding regimes, leading to improved growth rates and minimized environmental impact. Another significant aspect of AI in fish farming is disease detection and prevention. Through image analysis and pattern recognition, AI algorithms can identify early signs of diseases, parasites, or abnormalities in fish appearance and behavior. This enables prompt disease diagnosis and targeted treatment, reducing the need for excessive use of antibiotics and chemicals while improving fish welfare. In summary, the integration of AI techniques in fish growth and health status monitoring holds great promise for the sustainability of aquaculture. By leveraging AI's capabilities in data analysis, pattern recognition, and predictive modeling, fish farmers can optimize their practices, enhance productivity, reduce environmental impact, and ensure the welfare of farmed fish. However, continued research, data sharing, and collaboration between scientists, industry stakeholders, and policymakers are essential for harnessing the full potential of AI in achieving a sustainable aquaculture industry.

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Keywords Artificial intelligence (AI) · Fish growth monitoring · Health status monitoring · Sustainable aquaculture · Predictive analytics · Real time monitoring

Introduction

Aquaculture, the farming of aquatic organisms, has become increasingly vital for meeting the growing global demand for animal protein and addressing food security challenges. As the aquaculture industry continues to expand, it faces various challenges, including optimizing fish growth and ensuring the health and well-being of the farmed fish populations. Sustainable aquaculture practices aim to minimize environmental impacts while maximizing productivity and profitability (Austin et al. 2022). In this context, the integration of artificial intelligence (AI) has shown great promise in revolutionizing fish growth optimization and health status monitoring, thereby contributing to the sustainability of aquaculture operations (Chen et al. 2023). AI refers to the development and application of computer systems capable of performing tasks that typically require human intelligence, such as learning, problem-solving, and decision-making (Dellermann et al. 2019). In the field of aquaculture, AI techniques offer opportunities for real- time monitoring, data analytics, predictive modeling, and decision support systems, which can significantly enhance the understanding and management of fish growth and health (Mustapha et al. 2021). This research paper provides a comprehensive review of the role of AI in fish growth and health status monitoring in the context of sustainable aquaculture. Aquaculture practices aim to maximize fish growth rates while minimizing feed inputs, energy consumption, and environmental impact. AI techniques such as machine learning, genetic algorithms, and deep learning have been employed to develop models for optimizing feeding strategies, identifying optimal environmental conditions, and predicting growth trajectories (Chen and Gu 2020). By analyzing historical growth data, these AI models can learn and adapt to optimize feed management, water quality control, and environmental monitoring, leading to improved growth performance and resource efficiency (Bagheri et al. 2019). In addition to growth optimization, AI plays a crucial role in monitoring the health status of farmed fish populations (Yue and Shen 2022). Disease outbreaks can have devastating impacts on aquaculture operations, resulting in economic losses and environmental consequences (Abdelrahman et al. 2023). However, the aquaculture industry faces several challenges, including optimizing fish growth and ensuring the health and well-being of farmed fish (Sornkliang and Tongdee 2022). Efficient monitoring techniques are vital for sustainable aquaculture practices, enabling early detection of diseases, optimizing feeding strategies, and minimizing environmental impacts (Wang et al. 2021a). Traditional monitoring methods in aquaculture often rely on manual observations, which can be time-consuming, labor-intensive, and prone to human error. Additionally, these methods may not provide real-time data, limiting the ability to respond promptly to changing conditions and potential health issues (Wu et al. 2022). Therefore, there is a growing need for advanced technologies to enhance fish growth and health monitoring in aquaculture. Artificial intelligence (AI) has emerged as a transformative technology with significant potential for revolutionizing aquaculture practices. AI encompasses a range of techniques that enable machines to mimic human intelligence, learn from data, and make autonomous decisions (Janiesch et al. 2021). By leveraging AI, aquaculture operators can access real-time data, predictive analytics, and decision support systems, leading to improved productivity, sustainability, and profitability (Panudju et al. 2023). Machine learning, a subset of AI, enables systems to learn from data and make predictions or decisions without explicit programming. It can analyze large datasets, identify patterns, and generate models that facilitate accurate predictions of fish growth and health status (Burke et al. 2021). Genetic algorithms, another AI technique, mimic natural selection processes to optimize feed compositions, feeding schedules, and environmental parameters to maximize fish growth (Luna et al. 2019). Deep learning, a branch of machine learning, employs neural networks to extract complex patterns and relationships from large datasets. It has proven successful in various computer vision tasks, making it valuable for automated fish health monitoring. Computer vision techniques, enabled by deep learning algorithms, can detect visual cues of diseases or abnormalities in fish behavior and appearance, enabling early detection and timely interventions (Li et al. 2023). AI-based techniques, including disease detection and diagnosis systems, early warning systems, and behavioral analysis, provide tools for rapid and accurate disease identification, enabling timely interventions and minimizing the spread of infections (MacIntyre et al. 2023). Furthermore, AI can be used for real-time environmental monitoring, allowing for the early detection of changes in water quality parameters that may impact fish health. While AI offers tremendous potential for sustainable aquaculture, there are challenges that need to be addressed. These challenges include data availability, the interpretability of AI models, ethical considerations, and the integration of AI systems into existing aquaculture practices (Abangan et al. 2023). Overcoming these challenges requires collaboration among researchers, industry stakeholders, and regulatory bodies to ensure the responsible and effective application of AI in aquaculture.

In total, the integration of AI in fish growth and health status monitoring has the potential to revolutionize sustainable aquaculture practices. By leveraging AI techniques, aquaculture operators can optimize fish growth, improve disease detection and management, and minimize environmental impacts (Mustapha et al. 2021). The review paper will focus on the application of AI techniques for optimizing fish growth, detecting and diagnosing diseases, and monitoring the health status of fish in aquaculture systems. This paper will also explore various AI techniques, including machine learning, computer vision, and data analytics, that have been employed in aquaculture research and industry practices. It will analyze how these techniques have contributed to improving fish growth rates, enhancing feed management and optimization, and enabling early detection and diagnosis of diseases. Additionally, the paper will discuss the use of AI for environmental monitoring and water quality control in aquaculture systems. Ultimately, the adoption of AI in aquaculture can contribute to the sustainable production of seafood, enhance productivity, and support global food security.

Sustainable aquaculture and its challenges (Fig. 1)

Sustainable aquaculture, also known as sustainable fish farming, refers to the production of aquatic organisms in a manner that minimizes environmental impact, preserves biodiversity, and ensures the long-term viability of the industry. It aims to meet the increasing global demand for seafood while mitigating the negative effects on natural ecosystems and maintaining social and economic benefits (Reyers and Selig 2020). However, sustainable aquaculture faces several challenges that need to be addressed to achieve its goals. Some of the key challenges are:

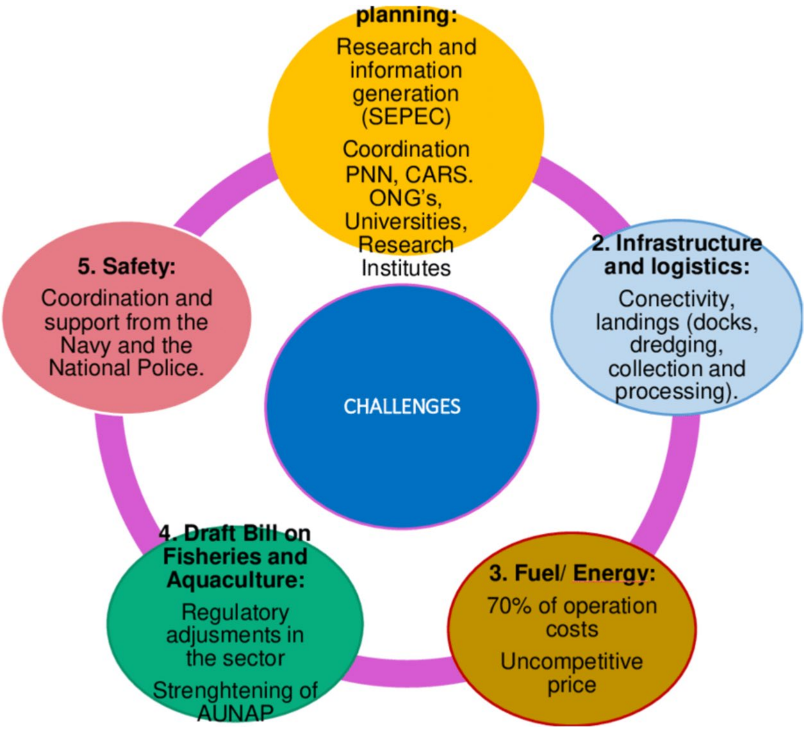

Fig. 1 Challenges on sustainable aquaculture (Rguez-baron 2019)

- Environmental impacts: Aquaculture operations can have significant environmental consequences, such as water pollution, habitat degradation, and the introduction of invasive species. Excessive nutrient discharge from fish waste and feed can lead to eutrophication and harmful algal blooms. Sustainable aquaculture requires minimizing these impacts and developing environmentally friendly practices (El-Sheekh et al. 2021).
- Disease management: Fish health is crucial for the sustainability of aquaculture. Disease outbreaks can cause significant economic losses and negatively impact wild fish populations if pathogens spread beyond the farm (Cascarano et al. 2021). Effective disease prevention, early detection, and management strategies are essential to maintain the health of farmed fish and prevent the transmission of diseases to wild populations (MacAulay et al. 2022).
- Feed sustainability: The reliance on fish-based feed ingredients, such as fishmeal and fish oil derived from wild-caught fish, raises concerns about overfishing and the depletion of marine resources (Henriksen 2020). Developing alternative and sustainable feed sources, such as plant-based and insect-based feeds, is essential to reduce the ecological footprint of aquaculture and maintain the balance in the marine food chain (Colombo et al. 2022).
- Genetic interactions: Escapes of farmed fish and their interbreeding with wild populations can have genetic consequences, including reduced genetic diversity and loss of locally adapted traits in wild populations (Wenne 2023). Preventing escapes and man-

aging the genetic interactions between farmed and wild fish are critical to maintain the integrity and resilience of wild populations (Thorstad et al. 2021).

- Resource use and efficiency: Aquaculture operations require significant amounts of water, energy, and other resources. Sustainable aquaculture aims to optimize resource utilization and minimize waste generation (Boyd et al. 2020). Improving production efficiency, water recirculation systems, utilizing renewable energy sources and offshore aquaculture can contribute to more sustainable practices (Bergman et al. 2020 and Austin et al. 2022).
- Social and economic considerations: Sustainable aquaculture should also address social and economic aspects, such as equitable distribution of benefits, fair labor practices, and the well-being of local communities (Cisneros-Montemayor et al. 2019). Ensuring that aquaculture operations provide socioeconomic benefits to local communities while respecting cultural values and supporting livelihoods is crucial for long-term sustainability (Troell et al. 2023).

Addressing these challenges requires a holistic and integrated approach that combines scientific research, technological innovation, policy development, and industry collaboration (Austin et al. 2022). The application of advanced technologies, such as artificial intelligence, can play a significant role in mitigating these challenges by enabling real-time monitoring, data-driven decision-making, and adaptive management strategies. By addressing these challenges, sustainable aquaculture can contribute to food security, reduce pressure on wild fish stocks, and promote the conservation of marine ecosystems.

Importance of aquaculture in food security (Fig. 2)

Aquaculture, or the farming of aquatic organisms such as fish, shellfish, and aquatic plants, plays a crucial role in ensuring global food security. As the world's population continues to grow, the demand for nutritious food increases, and aquaculture provides a sustainable solution to meet this demand (Duarte et al. 2022). The importance of aquaculture in food security can be understood through the following points:

- Increasing protein production: Aquaculture contributes significantly to global protein production, particularly in regions where alternative protein sources, such as livestock, are limited (Sandström et al. 2022). Fish and other aquatic organisms are excellent sources of high-quality protein, essential fatty acids, vitamins, and minerals. By cultivating aquatic species, aquaculture provides an efficient means of producing protein-rich food (Kandathil Radhakrishnan et al. 2020).
- Diversification of food sources: Aquaculture diversifies the sources of food production, reducing reliance on traditional agriculture and wild fisheries. This diversification helps to alleviate pressure on land-based food production systems and wild fish stocks. It provides an alternative source of nutritious food, reducing the vulnerability of communities to food shortages and price fluctuations (Choudhury et al. 2022).
- Improved food availability and accessibility: Aquaculture helps increase the availability of fish and seafood products, making them more accessible to populations that may have limited access to marine resources (Clavelle et al. 2019). By establishing fish farms in inland areas or near coastal communities, aquaculture enhances local food security by providing a consistent and reliable source of seafood.

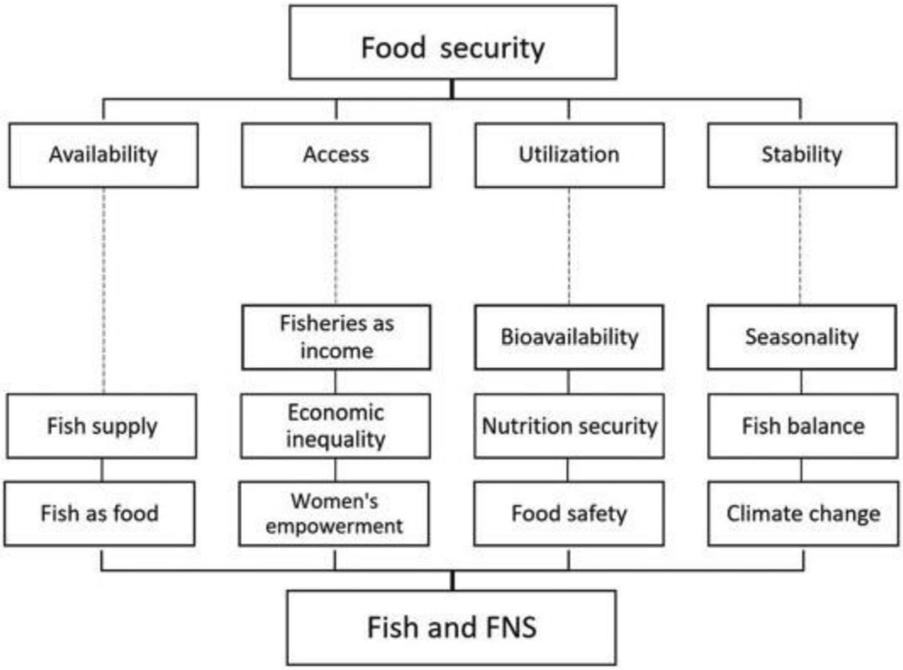

Fig. 2 Aquaculture for food security (Hasselberg et al. 2020)

- Sustainable resource use: Aquaculture can be conducted in a more sustainable manner compared to traditional fishing methods. It allows for controlled and responsible production, reducing the pressure on wild fish populations and ecosystems. By cultivating fish and other aquatic organisms, aquaculture reduces overfishing, promotes biodiversity conservation, and preserves marine habitats (Sampantamit et al. 2020).
- Economic development and employment opportunities: Aquaculture contributes to economic growth and rural development by generating employment opportunities, particularly in coastal and rural areas (Barua et al. 2022). It supports livelihoods and income diversification for small-scale farmers and fishing communities. By fostering local economies, aquaculture plays a vital role in poverty reduction and improving the overall well-being of communities (Troell et al. 2023).
- Climate change resilience: Aquaculture can be adapted to climate change impacts more effectively than traditional fisheries. It offers opportunities to develop resilient farming systems, such as integrated multi-trophic aquaculture, where waste from one species becomes nutrients for another (Correia et al. 2020). Aquaculture systems can also be designed to minimize greenhouse gas emissions, conserve water resources, and adapt to changing environmental conditions (Austin et al. 2022).

To maximize the benefits of aquaculture for food security, it is crucial to ensure that it is practiced in a sustainable and responsible manner. This involves addressing environmental impacts, improving feed efficiency, enhancing disease management, and promoting responsible governance and regulatory frameworks. By embracing sustainable aquaculture practices, it is possible to enhance food security, support economic development, and conserve natural resources for future generations (Austin et al. 2022).

Challenges in fish growth and health monitoring (Fig. 3)

Fish growth and health monitoring in aquaculture face several challenges that need to be addressed to ensure optimal fish production and well-being. Some of the key challenges in fish growth and health monitoring are:

- Early disease detection prevention and management: Diseases are a significant concern in aquaculture and can cause substantial economic losses. The prevention, early detection, and effective management of diseases are crucial for maintaining fish health (Diwan et al. 2022 and MacAulay et al. 2022). However, identifying specific pathogens, developing accurate diagnostic tools, and implementing appropriate disease management strategies can be challenging due to the diverse nature of aquatic pathogens and their interactions with the environment (Sonu and Chaudhary 2022; Mandal and Ghosh 2023).
- Environmental monitoring and water quality control: Water quality plays a vital role in fish growth and health. Poor water quality, including factors like dissolved oxygen levels, temperature, pH, and pollutants, can negatively impact fish health and growth rates. Monitoring and maintaining optimal water quality parameters throughout the aquaculture system can be challenging, particularly in large-scale operations or in areas with limited access to clean water sources (Jan et al. 2021).
- Feed management and optimization: Proper nutrition is essential for fish growth and health. Developing appropriate feeding regimes, optimizing feed formulation, and ensuring efficient feed utilization are critical challenges in aquaculture (Munguti et al. 2021). Achieving the right balance between providing adequate nutrition to promote growth and minimizing waste and environmental impact requires a thorough understanding of fish species-specific nutritional requirements and the availability of sustainable feed sources (Bava et al. 2019).
- Individual fish monitoring: Monitoring the growth and health of individual fish within a large population can be challenging. Traditional methods, such as manual measurements or visual inspection, are time-consuming, labor-intensive, and may not provide accurate or real time information (Kumar et al. 2022). Developing non-invasive and automated

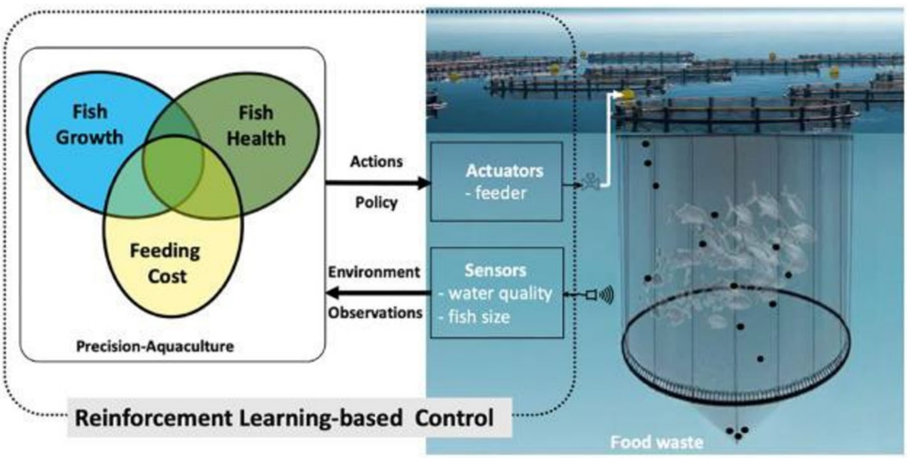

Fig. 3 Fish growth tracking using AI (Chahid et al. 2022)

monitoring techniques that can assess individual fish growth, behavior, and health status in a cost-effective and efficient manner is a significant challenge (An et al. 2021).

- Data management and analysis: Monitoring fish growth and health involves collecting and analyzing large amounts of data from multiple sources, such as water quality sensors, feeding systems, and health diagnostics. Managing and analyzing this data effectively can be complex and requires appropriate infrastructure, data integration, and advanced analytics techniques. Incorporating artificial intelligence and machine learning algorithms can help in processing and interpreting the vast amount of data generated, leading to more accurate and timely insights (Javaid et al. 2023).
- Standardization and regulatory compliance**:** The aquaculture industry operates under various regulations and standards to ensure the health and welfare of farmed fish and to minimize environmental impacts (Van de Vis et al. 2020). However, achieving consistent and standardized monitoring practices across different regions and farms can be challenging. Ensuring compliance with regulations, maintaining data accuracy, and implementing uniform protocols for fish growth and health monitoring are essential challenges that need to be addressed (Mantri et al. 2023).

Addressing these challenges requires continuous research and development, collaboration between researchers, industry stakeholders, and policymakers, and the adoption of innovative technologies. Advancements in sensor technologies, remote monitoring systems, data analytics, and artificial intelligence can play a crucial role in overcoming these challenges and improving fish growth and health monitoring in aquaculture practices.

Need for advanced monitoring techniques

The need for advanced monitoring techniques in aquaculture is driven by the increasing complexity and scale of aquaculture operations, the desire for sustainable practices, and the need to optimize fish growth and health. Advanced monitoring techniques offer several advantages over traditional methods and play a crucial role in addressing the challenges faced by the aquaculture industry (Saad et al. 2021). Some of the key reasons for the need for advanced monitoring techniques are:

- Real-time and continuous monitoring: Advanced monitoring techniques enable real- time and continuous data collection, allowing for immediate detection of changes or anomalies in fish growth, behavior, and environmental conditions (Ubina and Cheng 2022). This real-time monitoring helps in early identification of potential issues, such as disease outbreaks or suboptimal water quality, enabling prompt intervention and preventive measures.
- Enhanced accuracy and precision: Traditional monitoring methods often rely on manual measurements or visual observation, which can be subjective and prone to human error. Advanced monitoring techniques, such as automated sensors, imaging systems, and non-invasive biometrics, provide more accurate and precise measurements of fish growth, health parameters, and environmental conditions (Gladju et al. 2022). This enables better decision- making and targeted interventions based on reliable and objective data.
- Large-scale and remote monitoring: Aquaculture operations can span large areas, making it challenging to monitor every individual fish or environmental parameter manually. Advanced monitoring techniques, such as remote sensing, satellite imagery, and unmanned aerial vehicles (UAVs), allow for large-scale monitoring of fish farms

and their surrounding environments (Mahrad et al. 2020). This enables comprehensive data collection, spatial mapping, and analysis, even in remote or inaccessible locations.

- Data-driven decision support: Advanced monitoring techniques generate large volumes of data, which can be analyzed using advanced data analytics, machine learning, and artificial intelligence algorithms (Kibria et al. 2018). By applying these techniques to the collected data, valuable insights and patterns can be extracted, enabling data-driven decision support systems (Wong and Wang 2003). This helps in optimizing feed management, disease prevention, water quality control, and overall operational efficiency.
- Sustainable resource management: Advanced monitoring techniques contribute to sustainable resource management by optimizing resource use and minimizing waste. Accurate monitoring of water quality parameters, feed intake, and growth rates allows for precise resource allocation and efficient use of feed, energy, and water (Cassman 1999). This reduces the ecological footprint of aquaculture operations and supports the development of sustainable practices.

Finally, advanced monitoring techniques are essential in aquaculture to enable real-time, accurate, and comprehensive monitoring of fish growth, health parameters, and environmental conditions. These techniques empower data-driven decision-making, support sustainable resource management, enhance disease prevention, and optimize operational efficiency. By embracing advanced monitoring techniques, aquaculture practices can achieve improved productivity, increased profitability, and enhanced environmental sustainability.

Artificial intelligence in aquaculture (Fig. 4)

Artificial intelligence (AI) has the potential to revolutionize various industries, including aquaculture. Aquaculture, also known as fish farming, involves the cultivation of fish, crustaceans, mollusks, and other aquatic organisms in controlled environments (Chauhan and Mishra 2022). By leveraging AI technologies, aquaculture practices can be enhanced in several ways. Here are some applications of AI in aquaculture:

- Data analysis and prediction: AI can analyze large volumes of data collected from various sources, such as environmental sensors, water quality monitors, and feeding systems. By using machine learning algorithms, AI can identify patterns and correlations within the data, allowing aquaculturists to make data-driven decisions (O'Donncha et al. 2021). For example, AI can predict optimal feeding times, growth rates, disease outbreaks, and environmental conditions for maximum productivity.
- Monitoring and surveillance: AI-powered cameras and image recognition techniques can be used to monitor fish behavior, feeding patterns, and overall health. By analyzing real-time video feeds, AI algorithms can detect abnormalities or signs of stress in the fish population (Mustapha et al. 2021). This enables early intervention, such as adjusting feeding regimes or treating diseases promptly.
- Water quality management: Maintaining optimal water quality is crucial for the health and growth of aquatic organisms. AI systems can continuously monitor parameters such as temperature, pH, dissolved oxygen, and nutrient levels (Kaur et al. 2023a). By integrating data from sensors and applying AI algorithms, aquaculturists can identify

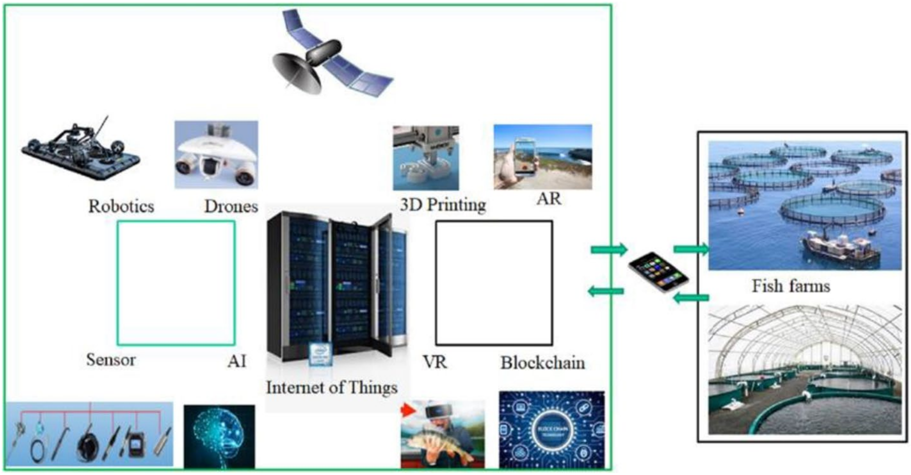

Fig. 4 Smart aquaculture system (Yue and Shen 2022)

deviations from the ideal conditions and take corrective measures in real time, thereby reducing the risk of fish mortality and improving overall productivity (Gladju et al. 2022).

- Inventory management: AI can assist in managing stock levels and inventory in aquaculture facilities. By analyzing growth rates, feeding patterns, and market demand, AI algorithms can provide insights into optimal stocking densities, harvest timings, and production planning (Gladju et al. 2022). This helps aquaculturists optimize resource utilization and maximize profitability.

Overall, AI has the potential to improve efficiency, sustainability, and productivity in aquaculture. By leveraging advanced analytics, real-time monitoring, and predictive capabilities, AI can empower aquaculturists with valuable insights and tools to make informed decisions and mitigate risks in fish farming operations.

Overview of artificial intelligence (Fig. 5)

Artificial intelligence (AI) refers to the development of computer systems capable of performing tasks that typically require human intelligence. AI systems are designed to simulate cognitive functions such as learning, reasoning, problem-solving, perception, and language understanding (Wu et al. 2021). AI technologies have made significant advancements in recent years, enabling machines to process and interpret vast amounts of data, recognize patterns, and make informed decisions.

AI can be broadly categorized into two types: Narrow AI and General AI.

A). Narrow AI: Also known as weak AI, narrow AI is designed to perform specific tasks within a limited domain. Examples of narrow AI include voice assistants like Siri and Alexa, recommendation systems, image recognition software, and autonomous vehicles (Prentice 2023). These AI systems excel at specific tasks but lack the broader cognitive abilities of human intelligence.

B). General AI: General AI, also referred to as strong AI or artificial general intelligence (AGI), represents AI systems that possess the ability to understand, learn, and apply

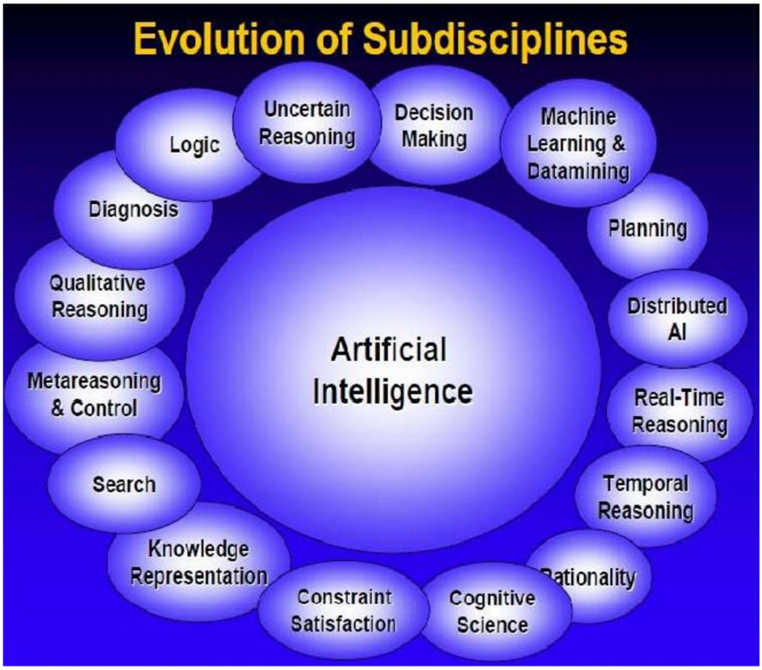

Fig. 5 Evolution of AI in aquaculture (Shukla Shubhendu and vijay 2013)

knowledge across multiple domains, much like a human being (Latif et al. 2023). General AI is hypothetical and remains an ongoing research goal.

Key components and techniques used in AI development:

- Machine learning (ML): Machine learning is a subset of AI that focuses on enabling systems to learn and improve from experience without being explicitly programmed. ML algorithms can identify patterns and make predictions or decisions based on training data. Supervised learning, unsupervised learning, and reinforcement learning are common approaches in ML (Sahoo et al. 2020).
- Deep learning: Deep learning is a subfield of ML that leverages artificial neural networks, inspired by the structure of the human brain. Deep learning algorithms, called neural networks, can process vast amounts of data and learn hierarchical representations, enabling them to perform complex tasks such as image and speech recognition (Sarker 2021).
- Natural language processing (NLP): NLP enables machines to understand, interpret, and generate human language. NLP techniques allow AI systems to process and analyze text, speech, and contextual information, enabling applications like language translation, sentiment analysis, and chatbots (Hariri 2023).
- Computer vision: Computer vision focuses on enabling machines to interpret and understand visual information from images or videos. AI systems employing computer vision can recognize objects, detect patterns, and analyze visual data, leading to applications like facial recognition, object detection, and autonomous vehicles (Kaur et al. 2022).

- Robotics: Robotics combines AI with physical systems to create intelligent machines that can interact with the physical world. Robotic systems often employ sensors, actuators, and AI algorithms to perceive their environment, make decisions, and manipulate objects (Beloev et al. 2021).
- Expert systems: Expert systems utilize knowledge representation and inference techniques to simulate human expertise in specific domains. These systems capture expert knowledge and provide recommendations or solutions based on that knowledge (Medsker and Bailey 2020).

The applications of AI are diverse and rapidly expanding across various industries, including healthcare, finance, manufacturing, transportation, agriculture, and entertainment. AI has the potential to revolutionize processes, improve efficiency, enable automation, enhance decision- making, and uncover insights from large datasets. However, the development and deployment of AI also raise ethical considerations, including privacy, transparency, bias, and the impact on employment. Addressing these challenges is crucial to ensuring that AI technologies are developed and used responsibly to benefit society as a whole.

AI techniques for fish growth optimization (Table 1)

Artificial intelligence (AI) techniques can be applied to optimize fish growth in aquaculture systems. These techniques can help enhance various aspects of fish growth, including feeding strategies, water quality management, disease detection and prevention, and overall farm management (Wang et al. 2021b).

Machine learning approaches

There are several machine learning approaches that can be used for fish growth optimization. These approaches leverage the power of data analysis and predictive modeling to identify key factors affecting fish growth and develop strategies to optimize it. Here are a few commonly used machine learning techniques in this context:

- Regression models: Regression models are commonly used to predict fish growth based on various input variables such as water quality parameters, feeding regimes, and environmental conditions. Techniques such as linear regression, decision trees, or random forests can be employed to model the relationship between these factors and fish growth (Wu et al. 2021). These models can provide insights into which variables have the most significant impact on growth and can be used to optimize feeding strategies, water quality management, and other factors affecting growth.
- Neural networks: Neural networks, particularly deep learning architectures, can be utilized to analyze complex and large-scale datasets related to fish growth. These models can capture intricate relationships between multiple input variables and fish growth, allowing for accurate predictions and optimization (Lashari et al. 2019). Convolutional neural networks (CNNs) can be employed for image-based analysis, such as assessing fish body condition or identifying diseases that may affect growth (Kaur et al. 2023b). Recurrent neural networks (RNNs) are useful for time-series data analysis, enabling the prediction of growth trajectories and identifying growth patterns.
- Genetic algorithms: Genetic algorithms can be employed to optimize fish growth by iteratively searching for the best combination of factors. These algorithms simulate the

Table 1 AI techniques in fish growth and health monitoring

Study	Objective	AI techniques	Key findings
1	Monitoring fish growth	Computer vision, machine learning	AI-based image analysis accurately measures fish length, weight, and biomass, enabling real-time growth monitoring and optimized feeding regimes
2	Disease detection and diagnosis	Deep learning, pattern recognition	AI algorithms detect subtle changes in fish behavior, appearance, and swimming patterns, allowing early identification of diseases and prompt treatment
3	Water quality management	Sensor data analysis, machine learning	AI models process data from sensors monitoring water parameters to predict optimal conditions for fish growth, minimizing stress and disease risks
4	Feeding optimization	Reinforcement learning, data analytics	AI systems learn and adapt feeding strategies based on environmental factors, fish behavior, and growth patterns, reducing feed waste and improving efficiency
5	Environmental impact assessment	Data mining, predictive modeling	AI tools analyze large datasets to assess the impact of aquaculture operations on surrounding ecosystems, aiding in sustainable practices and mitigation strategies
6	Early mortality prediction	Decision trees, data analytics	AI models integrate various factors like water quality, feeding patterns, and environmental conditions to predict and prevent fish mortalities
7	Automated fish counting	Computer vision, image processing	AI algorithms automate fish counting in aquaculture tanks or ponds, providing accurate population estimates and facilitating efficient management
8	Disease outbreak prediction	Bayesian networks, data analytics	AI models utilize historical disease data and environmental factors to forecast disease outbreaks, enabling proactive management and prevention
9	Growth prediction models	Neural networks, regression analysis	AI-based growth models predict fish growth trajectories based on historical data, aiding in production planning and optimizing resource allocation
10	Behavior analysis and welfare assessment	Pattern recognition, data analytics	AI systems monitor fish behavior patterns, assessing welfare indicators and identifying abnormal behavior that may signal health issues or stress

process of natural selection and evolution, generating a population of potential solutions and iteratively improving them over multiple generations (Albadr et al. 2020). For example, genetic algorithms can be used to optimize feeding schedules, determining the appropriate amount and composition of feed at different stages of growth, to maximize fish growth rates (Luna et al. 2019).

- Reinforcement learning: Reinforcement learning is a machine learning approach that involves an agent learning how to make decisions in an environment to maximize a reward signal. In the context of fish growth optimization, reinforcement learning can be used to determine the optimal feeding strategy (Gladju et al. 2022). The agent interacts with the environment (e.g., fish tank) and learns which actions (e.g., feed amount, frequency) result in the highest growth rates (Aljehani et al. 2023). By optimizing the feeding strategy over time, the agent can maximize fish growth.
- Bayesian optimization: Bayesian optimization is a sequential model-based optimization technique that is particularly useful when the evaluation of each potential solution is time- consuming or expensive. It can be used to optimize parameters affecting fish growth, such as water temperature, pH levels, or stocking density (Zaki et al. 2023). By iteratively exploring the parameter space and using a surrogate model to predict the growth outcome, Bayesian optimization can efficiently identify the best parameter settings for fish growth (Chiu et al. 2022).

These are just a few examples of machine learning approaches that can be used for fish growth optimization. The choice of approach depends on the available data, the complexity of the problem, and the specific goals of the optimization process. It's important to note that while machine learning can provide valuable insights and optimization strategies, domain expertise and careful experimental design remain crucial for successful implementation in aquaculture settings.

AI techniques for fish health status monitoring (Table 1)

AI techniques can play a significant role in monitoring the health status of fish in aquaculture settings. By analyzing various data sources and patterns, these techniques can help detect early signs of diseases, assess overall fish health, and enable timely intervention.

Disease detection and diagnosis (Fig. 6)

AI techniques can be effectively employed for disease detection and diagnosis in fish, helping aquaculturists and researchers identify and address health issues in a timely manner. Here are some AI techniques commonly used in this context:

- Image recognition and computer vision: Fish diseases often manifest as visual symptoms on the fish's body, such as lesions, discoloration, or abnormal behaviors. Image recognition and computer vision techniques, including deep learning models like convolutional neural networks (CNNs), can be used to analyze images or videos of fish and automatically detect signs of diseases (Zhang et al. 2020). These models can learn from labeled datasets and classify fish images into healthy or diseased categories, aiding in the early detection of diseases.

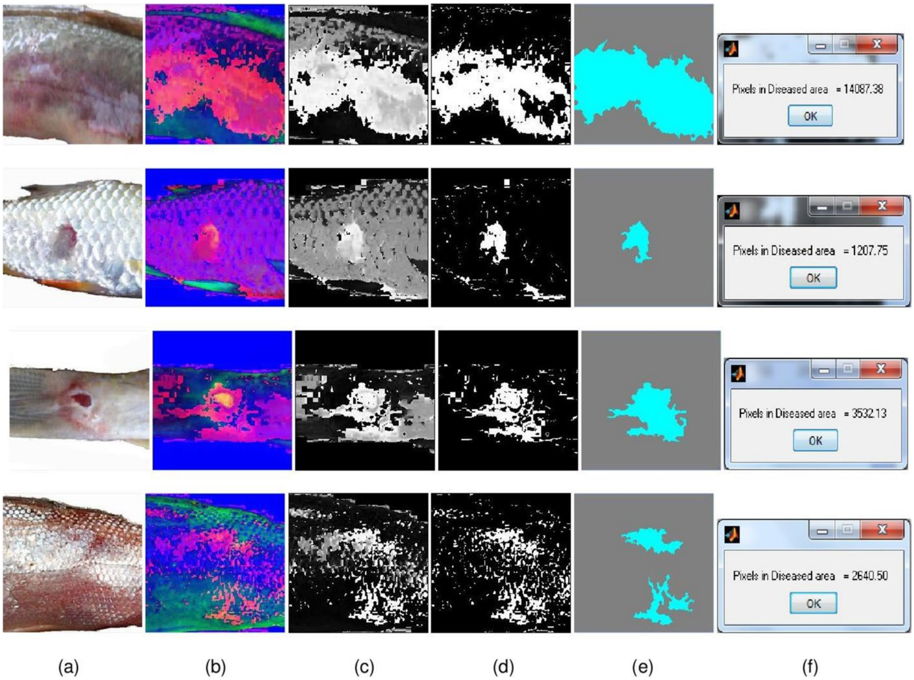

Fig. 6 AI in fish disease detection (Paul 2015)

- Pattern recognition and anomaly detection: AI algorithms can analyze patterns in fish health data to identify anomalies or deviations from normal conditions. This can involve monitoring water quality parameters, such as temperature, pH, ammonia levels, or dissolved oxygen, along with other variables like fish behavior or feeding patterns (Kaur et al. 2023b). By applying pattern recognition techniques, such as clustering algorithms or autoencoders, abnormal patterns can be detected, indicating potential diseases or stress conditions in fish populations.
- Expert systems and rule-based approaches: Expert systems combine domain knowledge and rules with AI techniques to diagnose fish diseases. These systems involve a knowledge base that includes information on various fish diseases, symptoms, and associated factors. By employing rule-based reasoning or decision tree algorithms, the system can ask specific questions about observed symptoms and guide the user to potential diagnoses and recommended actions for treatment or prevention (Nagaraj and Deepalakshmi 2022).
- Support vector machines (SVM) and classification algorithms: SVM and other classification algorithms can be used to analyze fish health data and classify fish into different disease categories. By training the models with labeled data representing healthy and diseased fish, the algorithms can learn to differentiate between various diseases based on input features such as water quality parameters, fish behavior, or molecular markers (González et al. 2023). These techniques can aid in accurate disease classification and subsequent treatment decisions.
- Time-series analysis and predictive modeling: Diseases in fish populations can exhibit temporal patterns and trends. Time-series analysis techniques, including autoregressive integrated moving average (ARIMA), recurrent neural networks (RNNs), or long short-term memory (LSTM) models, can be employed to analyze historical health data and

predict future disease outbreaks (ArunKumar et al. 2022). By considering factors such as environmental conditions, water quality, and past disease occurrences, these models can provide valuable insights for disease prevention and management.

It is important to note that AI techniques for fish disease detection and diagnosis are most effective when combined with domain expertise and validation from experienced aquaculturists or veterinarians. Integration of AI-based systems with real-time monitoring technologies, such as sensors or underwater cameras, can provide continuous surveillance and prompt detection of diseases, enabling early intervention and mitigation of potential losses in aquaculture operations.

Environmental monitoring

Artificial intelligence (AI) techniques can be utilized for environmental monitoring of fish to gather real-time data, analyze it, and make informed decisions for maintaining optimal conditions for fish health and well-being. Here are some AI techniques commonly employed for environmental monitoring of fish:

- Sensor data analysis: AI algorithms can process data collected from various sensors to monitor water quality parameters such as temperature, pH, dissolved oxygen levels, ammonia concentration, and turbidity. Machine learning models can be trained to recognize patterns and detect anomalies in sensor readings, providing early warnings for potential environmental issues that could impact fish health (Manoj et al. 2022).
- Image and video analysis: AI techniques, including computer vision, can analyze images or video feeds from cameras installed in fish tanks or ponds. These models can identify fish behavior patterns, detect signs of stress or disease, and monitor feeding activities. Additionally, image analysis can be used for automated fish counting and size estimation, providing valuable information for population management (Yang et al. 2021).
- Acoustic monitoring: AI algorithms can process underwater acoustic data to monitor fish behavior, migration patterns, and communication signals. Acoustic monitoring can help assess fish abundance, identify spawning grounds, and detect abnormal behavior or environmental disturbances (Li et al. 2022).
- Data fusion and integration: Environmental monitoring often involves collecting data from multiple sources, such as sensors, weather stations, and satellite imagery. AI techniques can integrate and analyze these diverse datasets to provide a comprehensive understanding of the fish habitat (Saleh et al. 2020). By combining data from different sources, it is possible to gain insights into the relationships between environmental factors and fish behavior or growth.
- Predictive modeling: AI models, such as machine learning algorithms, can analyze historical environmental data along with fish growth and health records to develop predictive models (Gladju et al. 2022). These models can forecast future environmental conditions, predict potential disease outbreaks, and optimize feed and water management strategies for maximizing fish growth.
- Decision support systems: AI techniques can be integrated into decision support systems for environmental monitoring of fish. These systems use real-time data, historical records, and predictive models to provide recommendations for optimal management decisions (Panudju et al. 2023). For example, AI-powered systems can

suggest adjusting feeding rates, modifying water flow, or initiating interventions based on real-time environmental conditions and fish health indicators.

- Autonomous underwater vehicles (AUVs): AI can be employed to enable AUVs to autonomously navigate underwater environments and collect environmental data. AUVs equipped with sensors and cameras can monitor water quality parameters, observe fish behavior, and gather data in remote or hazardous areas. AI algorithms can process the collected data in real-time and transmit the information to the monitoring system (Ubina and Cheng 2022).

These AI techniques enable continuous monitoring, real-time analysis, and proactive decision- making for maintaining a healthy environment for fish. By leveraging AI, environmental monitoring can become more efficient, accurate, and responsive to changes, ultimately promoting sustainable aquaculture practices.

Water quality monitoring

AI techniques can play a significant role in water quality monitoring for fish by automating the analysis of water parameters and alerting fish farmers to potential issues. Here are some AI techniques commonly used in water quality monitoring for fish:

- Sensor data analysis: AI algorithms can process real-time data from various sensors measuring water parameters such as temperature, pH, dissolved oxygen, ammonia, nitrate, and turbidity (Premkkumar et al. 2023). By applying techniques such as anomaly detection or pattern recognition, AI can identify abnormal readings or deviations from the optimal range, indicating potential water quality issues that may affect fish health and growth.
- Machine learning models: Machine learning algorithms can be trained on historical water quality data to develop predictive models. These models can forecast water quality trends and predict future values of key parameters based on historical patterns and other influencing factors (Wang et al. 2021a, b). By monitoring these predictions, fish farmers can proactively take preventive measures to maintain optimal water conditions for their fish.
- Image analysis: AI techniques, including computer vision, can analyze images or videos of the fish tanks or ponds to detect visual cues related to water quality. For example, changes in water color, presence of algae, or unusual fish behavior can be indicators of poor water quality. Convolutional neural networks (CNNs) can be trained to recognize and classify these visual patterns, alerting fish farmers to potential issues in real-time (Ben Tamou et al. 2021).
- Decision support systems: AI can be integrated into decision support systems for water quality management. By combining data from various sources, such as environmental data, water quality measurements, and fish health records, AI can provide recommendations on optimal actions to improve water quality based on predefined rules or learned patterns (Gladju et al. 2022). These systems can assist fish farmers in making informed decisions to maintain optimal conditions for fish growth.
- Internet of Things (IoT) integration: AI can be coupled with IoT devices and networks to create a connected water quality monitoring system. IoT sensors can collect data from multiple locations within the fish farm, and AI techniques can analyze this data in

real-time. By leveraging AI algorithms, fish farmers can gain insights into water quality variations across different areas and identify potential hotspots of water quality degradation (Agossou 2021).

- Data fusion and integration: AI can help integrate data from multiple sources, such as sensor data, satellite imagery, weather data, and historical records, to provide a comprehensive understanding of water quality dynamics. By combining these diverse datasets, AI can identify correlations and patterns that may not be evident through manual analysis alone, improving the accuracy and effectiveness of water quality monitoring (Haluza and Jungwirth 2023).

Overall, AI techniques can enhance water quality monitoring for fish by automating data analysis, enabling real-time detection of anomalies, and providing actionable insights to fish farmers. These technologies have the potential to optimize fish farming practices, minimize the risk of water quality-related issues, and improve fish health and growth outcomes.

Applications of AI in fish growth optimization (Table 2) (Fig. 7)

Feed management and optimization

AI can be applied to feed management and optimization in fish farming to improve feeding efficiency, reduce costs, and optimize fish growth. Here are some key applications of AI in this domain:

- Feed formulation: AI can assist in optimizing the formulation of fish feed by considering various factors such as fish species, nutritional requirements, feed ingredients, and cost constraints (Glencross et al. 2023). Machine learning algorithms can analyze historical feeding data, growth rates, and nutrient composition to identify optimal feed formulations that meet the nutritional needs of the fish while minimizing costs (Siad and Bouzid 2023). These models can also take into account environmental conditions and feeding behaviors to customize feed formulations for different stages of fish growth.
- Real-time feed monitoring: AI techniques can be used to monitor feed consumption in real-time. Computer vision algorithms can analyze video feeds or images of fish tanks or ponds to estimate feed intake by tracking the movement and behavior of fish during feeding (Zhang et al. 2023). This information helps fish farmers assess feed utilization and adjust feeding strategies accordingly, ensuring that the right amount of feed is provided to the fish.
- Feeding optimization: AI can optimize feeding strategies by analyzing various factors such as fish behavior, growth rates, and environmental conditions. Reinforcement learning algorithms can be employed to develop intelligent feeding policies by learning from interactions with the environment (Xia et al. 2021). These algorithms can adjust feed delivery schedules, quantities, and frequencies to maximize fish growth while minimizing feed waste and the risk of overfeeding.
- Environmental monitoring: AI techniques can integrate environmental data such as water temperature, dissolved oxygen levels, and water quality parameters with feeding data to assess the impact of environmental conditions on fish feeding behavior and

Table 2 AI in fish growth optimization

Application	Description
Feeding optimization	AI algorithms analyze fish behavior and feeding patterns to optimize the timing, quantity, and composition of feed for maximum growth and efficiency
Water quality monitoring	AI-based systems monitor various water parameters, such as temperature, pH, oxygen levels, and turbidity, to maintain optimal conditions for fish growth
Disease detection	AI algorithms analyze fish behavior, images, and sensor data to identify signs of diseases or abnormalities, enabling early detection and timely intervention
Environmental modeling	AI models simulate and predict the impact of environmental factors, such as temperature, salinity, and water flow, on fish growth, allowing for optimal farm design and management
Genetic optimization	AI algorithms assist in genetic selection and breeding programs by analyzing genetic data to identify traits that contribute to better growth rates and disease resistance
Stock management	AI-based systems track and monitor fish populations, growth rates, and biomass distribution, facilitating efficient stock management and decision-making
Harvest planning	AI models predict the optimal time for fish harvest based on growth rates, market demand, and economic factors, optimizing yield and profitability
Feed conversion ratio	AI algorithms analyze feeding data and fish growth rates to calculate and optimize the feed conversion ratio, reducing waste and improving efficiency
Disease treatment	AI systems aid in identifying and recommending appropriate treatments for fish diseases based on symptom analysis, historical data, and expert knowledge
Growth rate prediction	AI models leverage historical data, environmental conditions, and genetic information to predict fish growth rates, aiding in farm planning and production forecasting

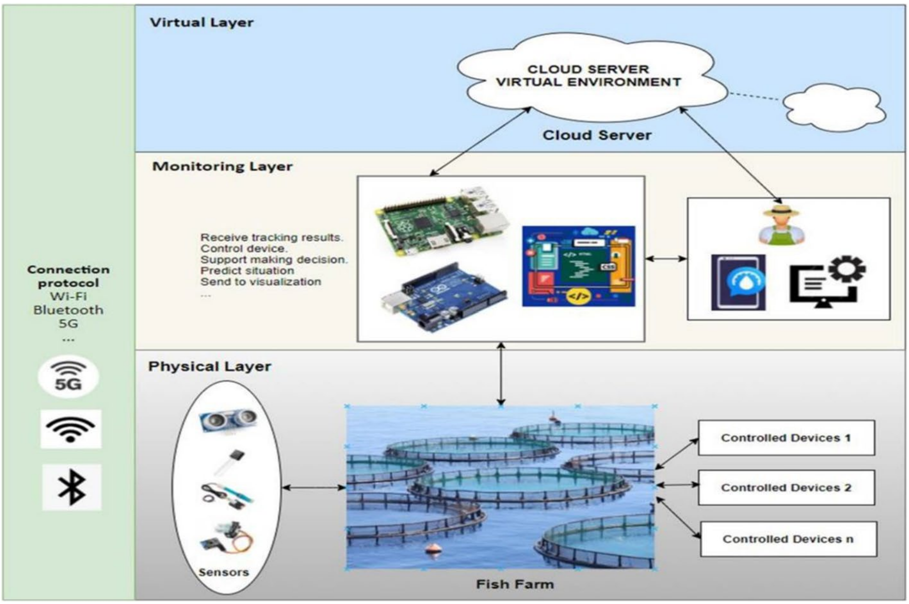

Fig. 7 AI in aquaculture optimization (Vo et al. 2021)

growth. Machine learning models can identify correlations between environmental variables and feeding patterns, helping fish farmers optimize feeding strategies based on the prevailing conditions (Chiu et al. 2022).

- Predictive modeling: AI can leverage historical data on fish growth, feed consumption, and environmental conditions to develop predictive models. These models can forecast future growth rates and feed requirements based on current conditions and historical trends. By providing accurate predictions, fish farmers can plan feed management strategies more effectively, optimizing feed supply and reducing waste (Mustapha et al. 2021).
- Automated feeding systems: AI can be integrated into automated feeding systems to optimize feed delivery based on real-time data. These systems can use machine learning algorithms to adaptively adjust feed quantities and feeding schedules in response to changes in fish behavior, growth rates, or environmental conditions (Hu et al. 2022). By continuously learning from data, these systems can improve feeding efficiency and reduce manual intervention.

The application of AI in feed management and optimization of fish can significantly improve efficiency, reduce costs, and optimize fish growth in aquaculture operations. By leveraging data analysis, machine learning, and automation, fish farmers can make informed decisions, ensure optimal nutrition, and enhance the overall productivity and sustainability of fish farming practices.

Water quality control

In the context of water quality control for fish, AI can be applied in several ways to ensure optimal conditions and prevent adverse effects on fish health. Here are some specific applications of AI in water quality control for fish:

- Real-time monitoring: AI algorithms can process real-time data from sensors measuring water quality parameters such as temperature, pH, dissolved oxygen, ammonia, and nitrate levels. By continuously analyzing these data streams, AI can detect anomalies or deviations from desired thresholds that may indicate poor water quality. Real-time monitoring allows for immediate response and corrective actions to maintain optimal conditions for fish (Vergina et al. 2020).
- Early warning systems: AI can be used to develop early warning systems that alert fish farmers to potential water quality issues before they escalate. By analyzing historical data patterns and correlations between water quality parameters and fish health, AI models can identify precursor signs that may lead to adverse conditions (Tung and Yaseen 2020). Early warnings enable proactive measures to be taken, such as adjusting water treatment, changing feeding strategies, or increasing aeration.
- Decision support systems: AI can be integrated into decision support systems that assist fish farmers in making informed decisions regarding water quality control. These systems can incorporate real-time data, historical records, and expert knowledge to provide recommendations on appropriate actions to optimize water quality parameters (Wu et al. 2021). AI algorithms can analyze the data and suggest specific interventions or adjustments to maintain the desired water quality conditions for fish.

- Adaptive control systems: AI-based adaptive control systems can automatically adjust environmental parameters based on real-time monitoring data. By utilizing machine learning techniques, these systems can learn the relationships between water quality parameters and fish responses (Deng et al. 2021). The control algorithms can then make dynamic adjustments to factors such as water temperature, oxygenation levels, or pH to maintain optimal conditions for fish growth and well-being.
- Predictive modeling: AI can be used to develop predictive models that forecast future water quality conditions based on historical data, environmental factors, and seasonal variations. By analyzing trends and patterns, AI models can predict potential fluctuations in water quality parameters, such as temperature changes or nutrient levels (Liao et al. 2021). Fish farmers can utilize these predictions to plan and implement preemptive measures to avoid adverse impacts on fish health.
- Optimization of water treatment processes: AI algorithms can optimize water treatment processes by analyzing large datasets and identifying the most effective treatment strategies. By considering factors such as water source characteristics, treatment methods, and desired water quality outcomes, AI can recommend optimal treatment processes to achieve the desired water quality conditions for fish (Abdallah et al. 2020).
- Data integration and analysis: AI techniques can integrate data from various sources, including sensor data, weather data, environmental data, and historical records, to gain a holistic understanding of water quality dynamics. By analyzing these diverse datasets, AI can identify correlations, trends, and patterns that may not be apparent through traditional analysis methods (Mondejar et al. 2021). This comprehensive analysis enhances the accuracy and effectiveness of water quality control strategies.

These AI applications in water quality control for fish enable fish farmers to maintain optimal conditions for fish growth, minimize stress and mortality rates, and enhance overall productivity and sustainability in aquaculture operations.

Environmental monitoring and modeling

AI has several applications in environmental monitoring and modeling for fish populations. It can help gather, analyze, and interpret large amounts of data, enabling more accurate and timely decision-making. Here are some specific applications of AI in this context:

- Data collection and analysis: AI can automate data collection from various sources, such as satellite imagery, sensor networks, and environmental databases. It can process and analyze these data to monitor environmental parameters relevant to fish populations, such as water quality, temperature, salinity, and ocean currents (Kume et al. 2021). AI algorithms can identify patterns, anomalies, and trends in the data, providing valuable insights into the health and habitat conditions for fish.
- Species identification and tracking: AI techniques, such as computer vision and image recognition, can be used to identify and track fish species. By analyzing underwater images or video footage, AI algorithms can automatically detect and classify different species, including endangered or invasive species (Er et al. 2023). This information is crucial for monitoring population dynamics, assessing biodiversity, and understanding the ecological impact of different fish species.
- Habitat mapping and modeling: AI can assist in mapping and modeling fish habitats. By analyzing environmental data, including water depth, temperature, and substrate

characteristics, AI algorithms can identify and predict suitable habitats for specific fish species. This information can aid in conservation efforts, restoration projects, and fisheries management by guiding decisions on habitat protection, enhancement, or restoration (Monteiro et al. 2021).
- Population modeling and forecasting: AI techniques, such as machine learning and statistical modeling, can be employed to develop population models for fish. By incorporating environmental variables, fishing pressure, and other relevant factors, these models can simulate and predict fish population dynamics over time (Senina et al. 2020). This information is valuable for assessing population sustainability, setting fishing quotas, and designing effective management strategies to ensure the long-term viability of fish populations.
- Disease detection and monitoring: AI algorithms can be used to detect and monitor diseases that affect fish populations. By analyzing physiological and behavioral data, such as changes in feeding patterns, swimming behavior, or skin coloration, AI can identify early signs of disease outbreaks (Gladju et al. 2022 and Fu et al. 2023). This enables prompt interventions, such as targeted treatment or quarantine measures, to mitigate the spread of diseases and minimize their impact on fish populations.
- Decision support systems: AI can be integrated into decision support systems for environmental management and fish population modeling. By combining real-time environmental data, historical records, and simulation models, AI-powered systems can provide recommendations for sustainable fisheries practices, habitat conservation, and ecosystem management (Polineni et al. 2022). These systems can aid policymakers, fishery managers, and conservationists in making informed decisions to protect fish populations and their habitats.

The application of AI in environmental monitoring and modeling for fish offers valuable insights and tools to improve our understanding of fish populations, their habitats, and the broader ecosystems they inhabit. By leveraging AI technologies, we can enhance conservation efforts, optimize fisheries management, and promote sustainable practices in fishery and aquaculture industries.

Benefits and limitations of AI in aquaculture

AI offers several benefits in aquaculture, but it also has certain limitations. Let's explore them:

Benefits of AI in Aquaculture:

- Increased efficiency: AI technologies automate various tasks in aquaculture, such as monitoring water quality, feeding regimes, and disease detection. This automation reduces the need for manual labor and improves operational efficiency, enabling farmers to manage larger- scale operations with fewer resources (Panda and Baral 2023).
- Improved decision-making: AI algorithms can analyze complex datasets and provide insights for better decision-making. By processing data from sensors, satellites, and historical records, AI can optimize feeding schedules, water quality management, and other factors that impact fish health and growth (Gladju et al. 2022). This leads to more informed and effective decision-making in aquaculture operations.

- Early disease detection: AI can detect early signs of disease in fish by analyzing behavioral patterns, physiological data, and environmental conditions. Early detection enables timely intervention, minimizing the spread of diseases and reducing economic losses for fish farmers (Barreto et al. 2022).
- Precision aquaculture: AI technologies enable precision aquaculture by optimizing production processes based on real-time data. Through monitoring and analysis, AI can adjust feeding, oxygenation, and other variables to meet the specific needs of fish populations, resulting in improved growth rates, feed conversion efficiency, and resource utilization (Chiu et al. 2022).
- Environmental sustainability: AI can contribute to sustainable aquaculture practices by optimizing resource usage and minimizing environmental impacts. By analyzing data on water quality, energy consumption, and waste management, AI algorithms can optimize operations to reduce the ecological footprint of aquaculture facilities (Alshater et al. 2023).

Limitations of AI in Aquaculture:

- Data availability and quality: The effectiveness of AI algorithms heavily depends on the availability and quality of data. In aquaculture, obtaining comprehensive and high-quality data can be challenging, especially in remote or offshore operations. Limited or inconsistent data can affect the accuracy and reliability of AI models (Aryai et al. 2021).
- Lack of domain-specific data: AI models require domain-specific data to be trained effectively. In some cases, aquaculture-specific datasets may be limited, making it difficult to develop robust and accurate AI models (Daniels et al. 2023). Collecting and labeling large- scale and diverse datasets for aquaculture applications can be time-consuming and resource- intensive.
- Model interpretability: Deep learning and complex AI models can often be seen as black boxes, making it challenging to interpret their decision-making process. In aquaculture, where decisions have significant implications for fish welfare and economic outcomes, interpretability is crucial for gaining trust and understanding the rationale behind AI-driven recommendations (Tsolakis et al. 2022).
- Cost and infrastructure requirements: Implementing AI technologies in aquaculture may involve upfront costs for sensors, data collection systems, computational resources, and skilled personnel. Small-scale fish farmers or those with limited resources may find it challenging to adopt AI due to the associated costs and infrastructure requirements (Mustapha et al. 2021).
- Ethical considerations: As with any technology, AI in aquaculture raises ethical considerations. For example, privacy concerns arise when collecting and storing sensitive data related to fish health, farming practices, or market intelligence. Ensuring proper data protection, informed consent, and ethical use of AI technologies are essential considerations in aquaculture applications (Dey and Shekhawat 2021).

It's important to note that while AI has immense potential in aquaculture, it should be seen as a tool that complements human expertise rather than replacing it entirely. A balance between AI-driven automation and human intervention is necessary to maximize the benefits and address the limitations of AI in aquaculture.

Conclusion

In conclusion, the role of AI in fish growth and health status monitoring is poised to revolutionize sustainable aquaculture practices. AI techniques offer significant potential for optimizing fish farming operations, improving productivity, and enhancing fish welfare while minimizing environmental impacts. By harnessing the power of machine learning, data analysis, and automation, AI enables real-time monitoring, early detection of diseases, precise feeding strategies, and proactive interventions to ensure optimal fish health and growth. AI- driven algorithms can analyze vast amounts of data from various sources, including environmental sensors, water quality measurements, fish behavior patterns, and genetic information. This data analysis enables the identification of key factors affecting fish growth, prediction of disease outbreaks, and the development of tailored strategies for optimized feeding, water quality management, and disease prevention. Moreover, AI technologies facilitate precise and targeted interventions, reducing resource wastage and minimizing the environmental footprint of aquaculture operations. Additionally, AI-driven autonomous systems and robotics hold promise for enhancing operational efficiency and reducing labor requirements in aquaculture. From underwater inspections and monitoring to automated feeding and sorting, AI-powered robots can streamline tasks, improve accuracy, and reduce human error. The future of AI in aquaculture lies in the integration of diverse data sources, interoperability of systems, and the development of decision support platforms. By integrating data from environmental monitoring, genetics, and market trends, AI can provide comprehensive insights and support informed decision-making. These advancements will foster sustainable aquaculture practices by optimizing resource utilization, mitigating environmental impacts, and promoting fish health and welfare. However, it is important to recognize that AI is a tool that should be combined with domain expertise and ethical considerations. Proper validation and calibration of AI models, data privacy, and maintaining human oversight are critical to ensure the responsible and effective use of AI in aquaculture.

Overall, the role of AI in fish growth and health status monitoring is central to achieving sustainable aquaculture. By harnessing the power of AI technologies, we can pave the way for efficient, environmentally friendly, and economically viable fish farming practices that meet the increasing global demand for seafood while ensuring the well-being of fish populations and their ecosystems.

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