Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming
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Chapter 3

Fish, Tech and Future: The Role of Automation and Digital Tools for Sustainable Tomorrow

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Abstract

The digital transformation of aquaculture is reshaping the sector by integrating advanced technologies that enhance efficiency and sustainability. This transformation is primarily driven by the adoption of Artificial Intelligence (AI), biological models and sophisticated data acquisition systems, which enable real-time monitoring and management of aquaculture operations. This chapter explores the applications of AI, robotics and biological models in various facets of aquaculture, highlighting their roles in enhancing productivity, sustainability and operational precision. AI-based solutions optimize feeding strategies, disease detection and water quality management by analyzing sensor data to ensure optimal conditions for fish growth and health, reducing manual intervention and minimizing environmental risks. Biological models simulate fish growth patterns, supporting informed decision-making, while IoT sensors and cloud computing enhance data acquisition, improving traceability and resource management. Robotics automate labour-intensive tasks, such as feeding and harvesting, with precision. Automated feeding systems, use robotic arms and computer vision, to precisely dispense feed based on fish feeding behavior, minimizing waste and ensuring optimal nutrition. Harvesting robots, guided by algorithms, sort and handle fish efficiently, reducing stress and enhancing yield quality. The integration of AI and robotics boosts operational efficiency, reduces labour costs and supports sustainable practices by optimizing resource use and minimizing environmental impacts. However, challenges like high initial investments, scalability and regulatory considerations remain significant. These technologies are advancing precision aquaculture, maximizing production outputs and environmental stewardship while reducing human intervention. Continued research and development are essential to address existing challenges and unlock the full potential of digital transformation in aquaculture.

Keywords Aquaculture, Capacity building, Education, Training

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1. Introduction

Fisheries play a critical role in global food security and economic development, contributing significantly to the livelihoods of millions. According to recent statistics, global fish production has steadily increased, with total production including capture fisheries and aquaculture reaching over 178 million tonnes annually. However, as demand for fish products continues to grow, the industry faces numerous challenges such as overfishing, environmental changes and resource management inefficiencies. To address these issues, the sector is increasingly embracing digitalization and automated technologies aligned with the principles of Industry 4.0 (Luna *et al.,* 2016). Industry 4.0 signifies the next stage of the industrial revolution, focusing on the integration of digital technologies, automation and data-driven decision-making. For fisheries and aquaculture, embracing these advanced technologies is vital to improving productivity, sustainability and resilience. Tools like AI-based monitoring systems, IoT-enabled sensors and smart feeding solutions provide real-time insights and analytics, enhancing operational efficiency while lowering labour costs and minimizing environmental impact. The transition to these technologies is not only a response to increasing production needs but also a strategic approach to ensure the future sustainability of fisheries in a rapidly changing environment.

2. Automation

Automation in aquaculture refers to the application of technology and machinery to perform tasks and processes in fish and seafood farming without direct human intervention (Li *et al.,* 2024). It encompasses a wide range of activities, from feeding and water quality management to data monitoring and harvesting. Automation is crucial in modern aquaculture due to its ability to enhance efficiency, precision and sustainability. It helps address challenges such as labour shortages, environmental concerns and the need for increased production. Automation in aquaculture systems refers to the integration of technology to manage and control various aspects of fish or aquatic organism farming. This can encompass several areas:

- *Feeding Systems*: Automated feeding systems can dispense precise amounts of feed at scheduled times, reducing labour and ensuring consistent feeding regimes that optimize the growth and health of the fish (Pratiwy *et al.,* 2022).
- *Water Quality Management*: Sensors can monitor parameters such as dissolved oxygen levels, pH, temperature and ammonia concentrations. Automated systems can adjust aeration and water flow, or initiate water exchanges to maintain optimal conditions.
- *Monitoring and Control*: Remote sensing technologies allow for real-time monitoring of environmental conditions and fish behavior. This data can be used to adjust parameters like water quality, feeding rates and environmental conditions automatically (Luna *et al.,* 2016).
- *Recirculating Aquaculture Systems (RAS)*: RAS relies heavily on automation to maintain water quality and manage waste. Automated filters, oxygenation

systems and waste removal mechanisms help maintain stable and clean water conditions (Saha *et al.,* 2018).

- *Harvesting and Sorting*: Automated systems can facilitate the harvesting process by sorting fish based on size or species, reducing handling stress and improving efficiency.

- *Health Monitoring*: Automated systems can detect early signs of disease through image recognition, water quality analysis, or behavioral changes, allowing for timely intervention and reducing losses.

- *Data Analytics and Decision Support*: Integration of automation with data analytics enables farmers to make informed decisions based on trends and predictive models, optimizing production efficiency and resource utilization (Li *et al.,* 2024).

2.1. Principles of Automation

Automation in aquaculture is guided by fundamental principles aimed at improving efficiency, precision and sustainability. It involves real-time data collection, automation systems rely on sensors and monitoring devices to continuously gather data on crucial parameters such as water quality, temperature and fish behavior. Integration of control systems, effective automation integrates various control systems, including feeding, water quality management and environmental control, to create a cohesive and responsive operation. Artificial intelligence (AI) decision-making, AI algorithms analyze the collected data to make informed decisions, optimizing resource allocation and farm management (Sasikumar *et al.,* 2024). Resource optimization and automation seek to optimize resource utilization, reducing waste and ensuring the efficient use of energy, water and feed. Error reduction, by minimizing human intervention, automation reduces the risk of human error, leading to more consistent and reliable results.

2.2. Procedures for Implementing Automation

- *Needs Assessment*: Begin by assessing the specific needs and challenges of the aquaculture operation. Identify areas where automation can bring the most significant benefits, such as feeding, water quality management, or data monitoring.

- *Technology Selection*: Choose appropriate automation technologies and equipment based on the identified needs. Consider factors like system compatibility, scalability and cost-effectiveness.

- *Integration*: Integrate the selected automation systems seamlessly into the aquaculture facility. Ensure that all components work together harmoniously and can communicate efficiently.

- *Monitoring and Control*: Establish a robust monitoring and control protocol to oversee automated processes. Regularly check system performance and make adjustments as necessary to optimize operations.

- *Maintenance*: Develop a proactive maintenance plan to ensure the continuous functionality of automation systems. Regular inspections, servicing and software updates are essential to prevent downtime.

- *Training*: Train aquaculture personnel to operate and troubleshoot the automation systems effectively. Knowledgeable staff are critical for maximizing the benefits of automation (Sasikumar *et al.,* 2024).

2.3. History of Automation in Aquaculture

1950s-1960s: Early automation in aquaculture focused on simple mechanical feeders and pond aeration systems.1970s-1980s: Introduction of basic sensor technologies for water quality monitoring. Automated fish-feeding systems gained popularity. 1990s-2000s: Advancements in sensor technology led to more accurate data collection and control systems. Automated fish grading and sorting systems were developed. 2010s-Present: Emergence of smart aquaculture systems using IoT and AI for real-time monitoring by robots for assessing fish health and underwater inspections like sediment and ocean floor inspections and decision-making (Simbeye *et al.,* 2018; Pratiwy *et al.,* 2022).

2.3.1. Milestones and Breakthrough

1970: First automated pond aerators were introduced, improving oxygen levels. 1995: Automated feeders with programmable timers became widely available. 2005: Adoption of sensors for monitoring water parameters such as pH, dissolved oxygen and temperature. 2012: The use of remote sensing and satellite technology for aquaculture monitoring (Simbeye *et al.,* 2018) expanded. 2018: AI-driven predictive analytics began to optimize feeding schedules and disease detection. 2020: Development of underwater robots for efficient monitoring and maintenance (Figure 1).

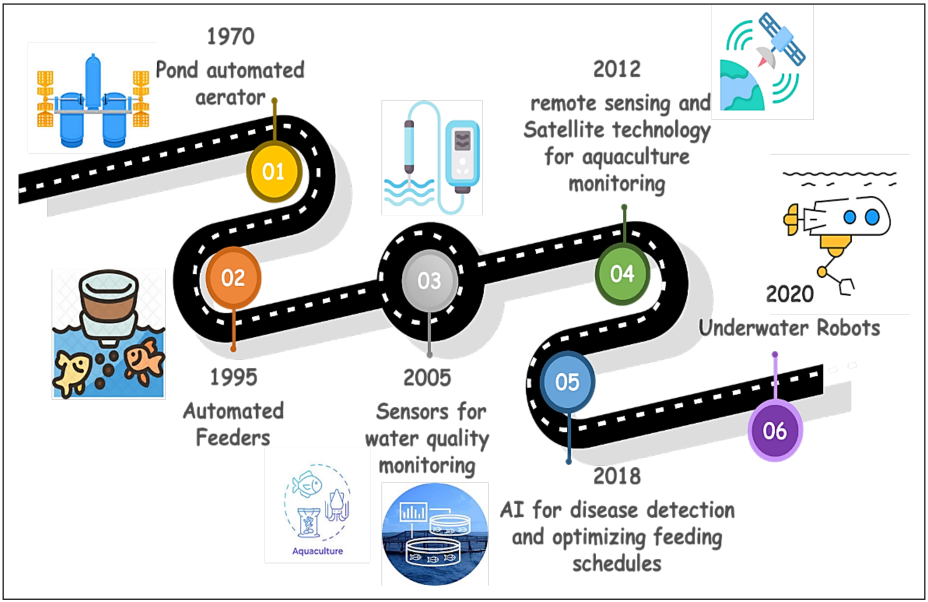

Figure 1: Key milestones in the history of aquaculture automation

2.4. Future Possibilities

Advancements in aquaculture leverage AI for decision-making, robotics for underwater tasks and automation in breeding and genetic programs. Integration with aquaponics promotes sustainable food systems, while automation reduces waste and enhances resource efficiency. These innovations drive smarter, eco-friendly practices, transforming aquaculture into a more efficient and sustainable industry (Figure 2).

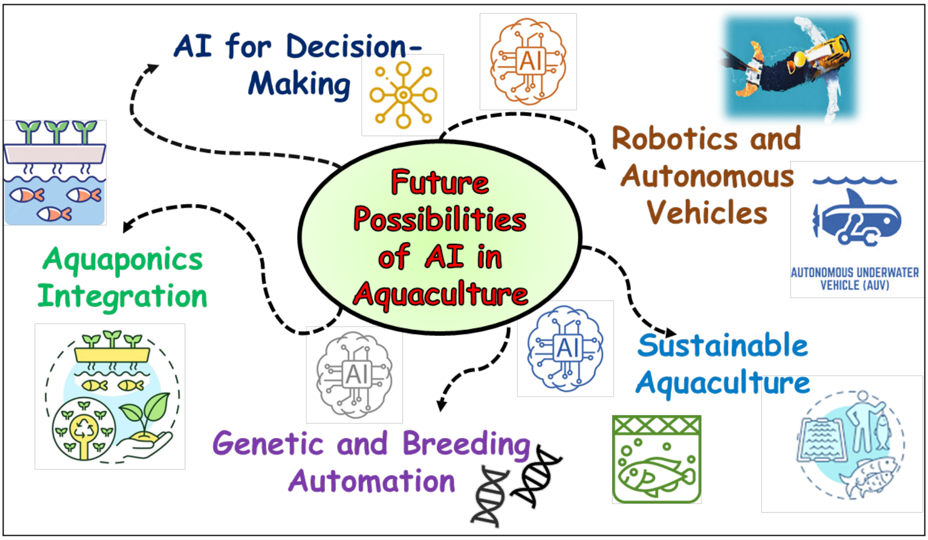

Figure 2: Future scope of Artificial Intelligence (AI) in aquaculture

- *AI for Decision-Making*: Advanced AI algorithms will play a pivotal role in optimizing operations, from feed management to disease control.
- *Robotics and Autonomous Vehicles*: Robots will perform underwater inspections, cleaning and maintenance tasks.
- *Genetic and Breeding Automation*: Automation may enhance selective breeding and genetic improvement programs.
- *Aquaponics Integration*: Automation will facilitate the integration of aquaculture with hydroponics or aquaponics systems.
- *Sustainable Aquaculture*: Automation will contribute to more sustainable and environmentally friendly practices by reducing waste and resource consumption (Pratiwy *et al.*, 2022).

3. Artificial Intelligence (AI)

Artificial intelligence (AI) is transforming industries worldwide and aquaculture is no exception. As global demand for seafood rises, the aquaculture sector faces challenges such as optimizing production efficiency, enhancing environmental sustainability and ensuring economic viability. AI technologies offer promising solutions by enabling precise monitoring, data-driven decision-making and automation of critical processes. In aquaculture, AI encompasses a range of applications, from real-time monitoring of water quality and fish health to optimizing feeding regimes and managing environmental factors. Machine learning algorithms analyze vast datasets collected from sensors, cameras and other sources, providing insights that traditional methods cannot match. These insights enable aquaculture operators to adjust parameters such as feeding schedules, water flow and oxygen levels dynamically, thereby improving growth rates, reducing disease risks and minimizing environmental impacts (Pratiwy *et al.,* 2022). Furthermore, AI-driven predictive models help anticipate challenges such as disease outbreaks or adverse weather conditions, allowing for proactive management strategies. Autonomous systems, including underwater drones and robotic platforms, contribute to enhancing monitoring and operational efficiency in aquaculture facilities, reducing labour costs and human error. While AI presents significant opportunities for innovation in aquaculture, challenges such as data privacy, regulatory frameworks and the need for specialized expertise must be navigated. By leveraging AI technologies effectively, the aquaculture industry can achieve sustainable growth while meeting the growing global demand for seafood.

3.1. Application of AI in Aquaculture

3.1.1. AI-based Feeding Device in Aquaculture Systems

An advanced AI feeding device has been developed by the Indonesian aquaculture company, e-Fishery (Li *et al.,* 2024). The system integrates motion sensors to monitor fish behavior and detect appetite levels, automatically dispensing feed when fish display signs of hunger. This innovation is capable of reducing feed costs by approximately 21%, enhancing feed efficiency and reducing waste. The technology includes proprietary software that allows fish farmers to remotely monitor feeding activities in real time and make adjustments as needed through their smartphones. Similarly, Observe Technologies offers an AI-based solution that tracks and analyzes feeding patterns in aquaculture systems. The platform provides objective data and empirical insights, guiding farmers on the optimal feed quantities required based on the real-time behavior of the fish and ensuring precise feed management. In Singapore and Japan, the aquaculture tech company has introduced the Umitron Cell, a smart feeding system controlled remotely. This device leverages data-driven decision-making algorithms to optimize feeding schedules, allowing farmers to customize feed distribution patterns, thereby improving the efficiency and sustainability of feeding practices.

3.1.2. AI-Driven Drones in Aquaculture

Autonomous drones equipped with advanced sensors can continuously monitor essential water quality parameters, such as turbidity, temperature, dissolved oxygen levels and even the physiological responses of fish, including heart rates (Simbeye *et al.,* 2018). These real-time data are transmitted to a centralized system, which can be accessed via smartphones or other digital devices, enabling efficient monitoring and management of aquaculture environments. Expanding on these innovations, researchers have developed a bio-inspired robotic system known as 'Shoal.' These autonomous robotic fish are designed to detect contaminants and monitor environmental health around aquaculture sites. Equipped with high-precision sensors, they navigate independently within the aquatic environment and communicate via low-frequency acoustic signals, enabling collective data gathering and coordinated responses to changes in water quality (Sasikumar *et al.,* 2024).

3.1.3. Disease Prevention in Aquaculture

The Norwegian Seafood Innovation Cluster launched an advanced cloud-based platform, AquaCloud, in April 2017 to support aquaculture farmers in mitigating the risk of sea lice infestations in net pens. By leveraging real-time data analytics and predictive modelling, the system effectively aids in reducing fish mortality rates and minimizing reliance on costly chemical or mechanical treatments for parasite control.

3.1.4. Artificial Intelligence in Shrimp Aquaculture

Eruvaka Technologies, based in India, provides AI-powered solutions specifically designed for shrimp aquaculture (Al-Hussaini *et al.,* 2018). These include real-time water quality monitoring, automated voice alerts, intelligent appetite-based feeding systems and autonomous aerator management. Deployed across around 1,000 hectares in regions such as Surat, Goa andhra Pradesh and Pondicherry, Eruvaka's innovations help optimize feeding efficiency and maintain ideal pond conditions. As a result, the technology enhances farm management, boosting both productivity and sustainability in shrimp farming.

3.1.5. Biomass Estimation

Minnowtech, a U.S.-based aquaculture technology company has developed a software-imaging platform to estimate shrimp abundance (Daoliang *et al.,* 2020; Li *et al.,* 2024). A sonar device collects data from shrimp ponds and provides farmers with a weekly biomass estimate. Tracking biomass enables farmers to better calculate average daily growth and feed conversion ratio.

3.1.6. Routine Stock Assessment in Aquaculture

AI-driven vision-based sensors facilitate real-time monitoring of cultured aquatic species by analyzing their swimming behavior, growth patterns and physical condition, including any injuries. One notable innovation is XperCount, an AI-powered device developed by the aquaculture technology company XpertSea (Karningsih *et al.,* 2021). This device employs machine learning algorithms and integrated camera systems to rapidly measure, count, image and size shrimp within seconds. The data collected is processed for comprehensive health assessments, enabling timely intervention and management of stock health.

3.1.7. AI in Open Sea Fisheries

The Global Fishing Watch Platform, an independent organization, has partnered with Google, Oceana and SkyTruth, non-profit digital mapping organization, to leverage AI and satellite imagery for tracking global fishing activities. This initiative enables precise monitoring of Illegal, Unreported and Unregulated (IUU) vessels, as well as detecting poaching, overfishing and at-sea transshipments (the transfer of catches between vessels). AI-based surveillance systems can also capture critical information on vessel dimensions and the types of fishing gear employed, facilitating enhanced regulation and sustainable fisheries management Li *et al.,* 2024).

3.1.8. AI for Conservation of Endangered Marine Species

AI-enabled drones equipped with visual sensors and high-resolution cameras are revolutionizing the monitoring of endangered fish populations by providing rapid and accurate habitat assessments. For larger marine species, such as sharks and humpback whales, researchers can deploy telemetry transmitters attached to their fins, allowing for real-time tracking and behavioral analysis. These technologies significantly enhance the efficiency of conservation efforts by enabling more precise data collection, contributing to improved strategies for protecting vulnerable marine fauna (Saha *et al.,* 2018).

3.2. Advantages of AI in Fisheries

The integration of AI technology in fisheries management enhances operational efficiency across the entire value chain, from hatchery operations to post-harvest processing. By employing predictive analytics, AI can accurately forecast potential threats, such as disease outbreaks or deterioration in water quality, enabling proactive measures to safeguard stock health (Al-Hussaini *et al.,* 2018). Additionally, AI applications can optimize feeding practices, water parameters and growth conditions, thereby maximizing production and minimizing resource wastage (Figure 3). AI systems, through continuous learning and adaptation, offer versatile solutions tailored to various aquaculture settings. These technologies not only streamline routine management tasks but also reduce the need for manual labour, thereby cutting operational costs. Furthermore, AI-driven monitoring and automation ensure greater product quality and uniformity by maintaining optimal environmental conditions and precision feeding, ultimately contributing to sustainable aquaculture practices.

3.3. Disadvantages of AI in Fisheries

The adoption of artificial intelligence in the fisheries and aquaculture sectors often requires substantial financial investment, which may be prohibitive for small and medium-scale operators. The initial setup costs, coupled with ongoing maintenance and software updates, can significantly strain financial resources. Furthermore, the integration of AI-driven automation systems can lead to reduced demand for manual labour, potentially displacing workers who rely on employment within these industries. Although these advancements may boost efficiency and profitability for farm owners, they pose socio-economic challenges for communities dependent on traditional

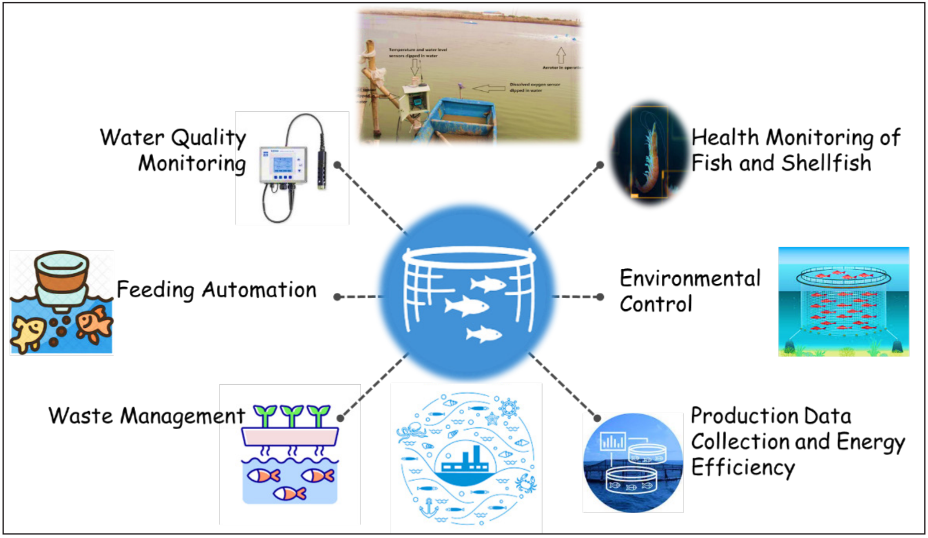

Figure 3: Key advantages and applications of AI in aquaculture systems

fisheries employment. To address this, it is crucial to implement policies and training programs aimed at reskilling the workforce, enabling them to take on new roles in managing and operating AI systems, thereby ensuring a balanced transition that benefits both productivity and social equity (Daoliang *et al.,* 2020).

4. Robotics

Robotics in aquaculture represents a burgeoning field where technological advancements are reshaping traditional farming practices. This integration of robotics offers novel solutions to challenges in labour efficiency, resource management and environmental sustainability within aquaculture operations (Vásquez-Quispesivana *et al.,* 2022). One of the primary applications of robotics in aquaculture is in automated feeding systems. These systems use robotic arms equipped with sensors and cameras to dispense precise amounts of feed based on real-time data on fish behavior and growth rates. By optimizing feeding schedules and reducing waste, robotic feeders contribute to improved feed conversion ratios and overall economic efficiency. Additionally, robotics play a crucial role in monitoring and maintaining water quality. Autonomous underwater vehicles (AUVs) equipped with sensors can navigate aquaculture facilities, collecting data on parameters such as dissolved oxygen levels, pH and temperature (Albalawi *et al.,* 2021). This continuous monitoring helps aquaculturists detect potential issues early, such as oxygen depletion or contamination, allowing for prompt corrective actions and reducing the risk of fish stress or mortality. Harvesting is another area where robotics shows significant promise. Automated systems can sort and harvest fish based on size, species, or maturity, minimizing handling stress and ensuring high-quality yields. Robotic harvesters not only enhance efficiency but also reduce reliance on manual labour, which can be costly and labour-intensive. Moreover, robotics contribute to sustainability efforts in aquaculture by reducing environmental impacts. Automated systems can optimize water usage, minimize feed waste and manage effluents more efficiently, thus mitigating potential pollution and resource depletion. While the adoption of robotics in aquaculture brings numerous benefits, challenges such as high initial costs, technological complexity and the need for specialized training and maintenance persist. Overcoming these challenges requires collaboration between technology developers, aquaculture operators and regulatory bodies to ensure the safe, effective and sustainable integration of robotics into aquaculture practices.

4.1. Novel Robotics Advances in Aquaculture

Robotics and AI innovations, such as autonomous vehicles, drones and automated systems, are transforming aquaculture by improving efficiency, monitoring and sustainability while enhancing fish health and optimizing critical tasks like feeding, cleaning and vaccination (Zhao *et al.*, 2021). There are many advanced underwater robots for various applications in the field of fisheries and aquaculture (Figure 4).

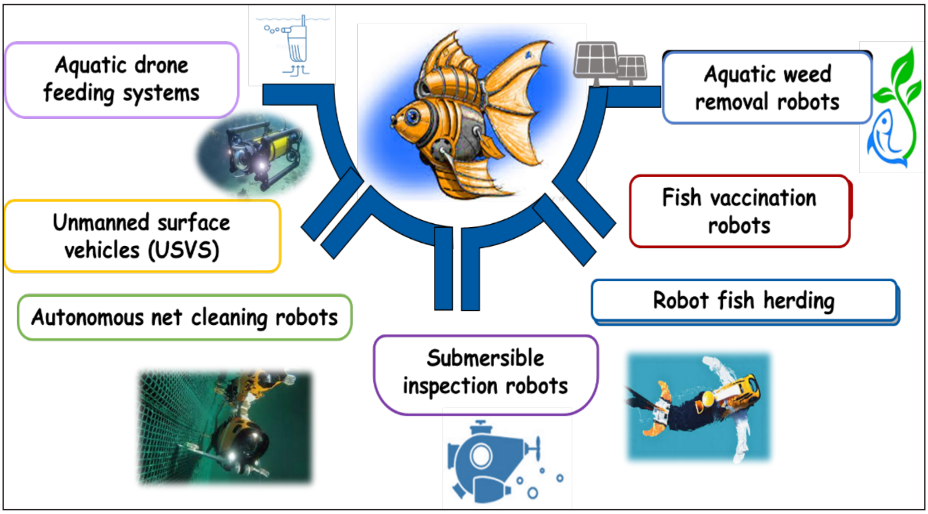

Figure 4: Various advanced underwater robots used in fisheries and aquaculture

4.1.1. Robot Fish Herding

An exemplary innovation in this field is the 'RangerBot', developed by the Queensland University of Technology, Australia. It is the world's first vision-based autonomous underwater robotic system engineered specifically for coral reef ecosystems. Equipped with advanced computer vision and machine learning algorithms, RangerBot is capable of monitoring critical reef health parameters such as coral bleaching, water quality and overall reef structure through precise mapping and inspection (Albalawi *et al.,* 2021). One of RangerBot's primary functions is the management of *Acanthaster planci* (crown-of-thorns starfish) populations, a significant coral predator threatening reef stability. By emulating the behavior of natural fish species, RangerBot can navigate complex reef terrains to locate and target these starfish (Vásquez-Quispesivana *et al.,* 2022). Upon detection, the robot deploys a lethal injection specifically formulated to eradicate the starfish without harming the surrounding marine environment, providing an ecologically sustainable method of controlling invasive species and protecting coral reef biodiversity.

4.1.2. Unmanned Surface Vehicles (USVS)

Example: Saildrone, a company that specializes in USVs, has developed autonomous sailboats equipped with various sensors for environmental monitoring. These USVs collect data on water quality, temperature and other relevant parameters in aquaculture settings, helping farmers make informed decisions about water management (Albalawi *et al.,* 2021).

4.1.3. Submersible Inspection Robots

Example: The "BlueROV2" by Blue Robotics. It is a remotely operated underwater vehicle (ROV) used for various tasks, including inspecting underwater infrastructure like cages and nets in aquaculture farms. Its HD cameras and lights allow operators to assess the condition of equipment and monitor fish health (Al-Hussaini *et al.,* 2018).

4.1.4. Underwater 3D Printing

Researchers are exploring underwater 3D printing technology for creating and repairing structures in aquaculture facilities. This technology can be used to produce custom components, such as coral nurseries or artificial reefs, to enhance the habitat for aquatic organisms. Underwater 3D printing enables the rapid construction of artificial reefs directly on-site, reducing the time and resources required for transportation and installation. This speed is particularly crucial in areas where natural reefs have been damaged or destroyed due to human activities or natural disasters (Karningsih *et al.,* 2021).

4.1.5. Aquatic Weed Removal Robots

Example: The "Weed-IT" robot, developed in the Netherlands, is designed to autonomously remove aquatic weeds from fish ponds and water bodies. Equipped with cameras and sensors, it identifies and targets the weeds, reducing the need for manual removal and chemical treatments (Teja *et al.,* 2020).

4.1.6. Autonomous Net Cleaning Robots

Example: Robots like the "Ecomerdenet Cleaner" and "Remora" (the first fully autonomous net cleaner and inspector) are specifically designed for cleaning fish nets in aquaculture operations (Yongqiang *et al.,* 2019). These robots use high-pressure water jets to remove fouling organisms and debris from the nets, ensuring water flow and maintaining the health of the fish.

4.1.7. Aquatic Drone Feeding Systems

Example: Companies like XpertSea have developed autonomous drone-based feeding systems equipped with cameras and AI algorithms. These drones can fly over aquaculture ponds, analyze fish behavior and feeding patterns and dispense the appropriate amount of feed to optimize growth rates and minimize waste (Kruusmaa *et al.,* 2020).

4.1.8. Fish Vaccination Robots

Example: Norwegian company Stingray Marine Solutions has developed an automated system known as the "Stingray" for vaccinating farmed salmon (Teja *et al.,* 2020). The robot identifies individual fish in a cage, positions them for vaccination and administers precise doses of vaccines, reducing stress and the risk of disease transmission. Different organizations and companies are involved in the development and deployment of robotics technologies for aquaculture.

4.1.9. Blue Robotics

Blue Robotics specializes in underwater robotics and provides remotely operated vehicles (ROVs) and components that are widely used in aquaculture for inspection and monitoring tasks.

4.1.10. Saildrone

Saildrone designs and deploys unmanned surface vehicles (USVs) equipped with various sensors for environmental monitoring, including applications in aquaculture.

4.1.11. Stingray Marine Solutions

Stingray Marine Solutions offers automated systems for fish vaccination in aquaculture, helping to improve fish health and reduce stress during the vaccination process (Lee, 1995).

4.1.12. Liquid Robotics (a subsidiary of Boeing)

Liquid Robotics develops autonomous marine robots, including Wave Gliders, which have applications in environmental monitoring and data collection for aquaculture (Kassem *et al.,* 2021).

4.1.13. C-Worker (by L3Harris) and Other AUV Manufacturers

Various autonomous underwater vehicle (AUV) manufacturers, such as L3Harris, offer AUVs for underwater inspection and data collection in aquaculture (Yongqiang *et al.,* 2019).

5. Data Acquisition Systems

Data acquisition systems are essentially tools that allow us to collect and analyze data from various sources within an aquaculture operation. This information provides valuable insights into the health and productivity of fish populations, water quality and overall system performance. By using these systems, we can make informed decisions that lead to increased efficiency, improved yields and ultimately, a more sustainable industry (Lee, 1995). Data acquisition systems are devices used to collect, process and store data from various sources in real-time. They can be thought of as the brain of any monitoring or control system, as they enable the system to gather information about its environment and respond accordingly. These systems typically consist of three main components: sensors to measure physical quantities such as temperature and pressure, a signal conditioning circuit to convert the sensor output into a suitable form for processing and a data acquisition device to capture the conditioned signal and store it in memory for subsequent analysis. The data can then be analyzed using specialized software to extract meaningful information about the system under observation (Albalawi *et al.,* 2021).

5.1. Benefits of Implementing Data Acquisition Systems

Increased efficiency, real-time monitoring allows farmers to make data-driven decisions and rapidly respond to changes in the environment. This improves yield and reduces costs. Improved animal welfare, with constant monitoring, farmers can detect and address potential threats before they become emergencies, ensuring that their animals are healthy and well-cared for. Sustainability gains, by reducing waste and optimizing resources, data acquisition systems can help farmers operate with a lower environmental impact (Daoliang *et al.,* 2020).

5.2. Types of Data Acquisition Systems in Aquaculture

There are several types of data acquisition systems used in aquaculture, each with its own unique set of functions and advantages. One such system is the sensor-based data acquisition system, which uses sensors to measure various environmental parameters such as water temperature, pH levels and dissolved oxygen (Vásquez-Quispesivana *et al.,* 2022). Another type of data acquisition system used in aquaculture is the remote monitoring system, which allows farmers to monitor their farms from a distance. This system typically includes cameras and other sensors that can be accessed remotely via a computer or mobile device. Remote monitoring systems are particularly useful for farmers who have multiple farms or who need to travel frequently, as they allow them to keep an eye on their operations from anywhere in the world. It is used in water quality monitoring, feed management, environmental conditions, fish behavior and health, fish behavior and health, remote monitoring, optimization and decision-making, regulatory compliance, research and development, energy efficiency, traceability and quality assurance (Karningsih *et al.,* 2021).

5.3. Real-World Examples of Data Acquisition Systems in Aquaculture

One example of a successful implementation of data acquisition systems in aquaculture is at a salmon farm in Norway. By using sensors to monitor water temperature, oxygen levels and fish behavior, the farm was able to optimize feeding schedules and reduce mortality rates by 20%. This not only improved production but also reduced costs associated with overfeeding and disease management (Kruusmaa *et al.,* 2020).

Another example is a shrimp farm in Thailand that implemented a data acquisition system to monitor water quality and detect early signs of disease. This allowed the farm to quickly respond and treat infected shrimp, reducing losses and improving overall yield. The system also helped to reduce water usage and improve sustainability practices (Kassem *et al.,* 2021).

6. Biological Models and Automatic Control Systems: The Future of Aquaculture.

As the world's population continues to grow, so does the demand for food. Aquaculture has become an increasingly important industry in meeting this demand and automatic control systems are essential for ensuring the efficient and sustainable production of aquatic organisms. Biological models play a crucial role in these automatic control systems (Zhao *et al.,* 2021). By using mathematical and computational models to simulate the behavior of living organisms, we can better understand and predict how they will respond to changes in their environment. This allows us to optimize the conditions in which they are raised, leading to healthier and more productive fish farms.

Biological models are simplified versions of intricate biological systems, designed to analyze and predict their behavior (Von Borstel *et al.,* 2013). In aquaculture, these models simulate fish growth, population dynamics and the interactions within aquatic ecosystems. Using mathematical equations and computer simulations, researchers can explore various scenarios and forecast the effects of different management approaches. The role of biological models in aquaculture is crucial, especially as demand for seafood rises and pressures on wild fish stocks intensify. As aquaculture becomes an essential food source, managing fish populations and preserving ecosystem health remains a complex challenge. Biological models serve as valuable tools to help researchers and managers better understand these processes and make well-informed decisions (Von Borstel *et al.,* 2013).

6.1. Types of Biological Models

There are several types of biological models used in aquaculture, each with their own unique characteristics and applications. One type is the empirical model, which is based on observations and measurements of real-world systems. These models are often used to predict the behavior of complex systems and can be used to optimize feeding strategies or water quality management. Another type of model is the mathematical model, which uses mathematical equations to describe the behavior of a system (Lee, 1995). These models are often used to simulate the effects of different environmental conditions or management practices on fish growth and health. Mathematical models can also be used to optimize feeding regimes or to design new aquaculture systems. Some of the biological models are growth models, nutrient cycling models, population dynamics models, disease spread models, feed conversation models, water quality models, behavioural models, ecological models, optimization models and multi-trophic models.

7. Advantages of Automation in Aquaculture

Increased efficiency, Automation streamlines tasks, leading to greater operational efficiency in feeding, monitoring and harvesting processes. Precision and consistency, automated systems ensure precise and consistent execution of tasks, reducing variability and improving overall productivity. Labor savings, automation reduces the dependency on manual labor, addressing labor shortages and minimizing operational costs. Data collection and analysis, automation provides real-time data collection, enabling data-driven decision-making for farm management and optimization. Reduced human error, automated processes minimize the risk of human errors, ensuring higher product quality and environmental compliance. Resource management, automation optimizes resource utilization, reducing waste and resource consumption, contributing to sustainability (Wu *et al.,* 2022). Environmental monitoring, continuous monitoring of water quality and conditions help maintain optimal environmental parameters and minimize environmental impacts. 24/7 operation, automation systems can provide round-the-clock monitoring and control, addressing issues promptly and reducing the risk of emergencies. Improved product quality, automation systems like sorting and grading ensure uniformity and high standards in the final product. Farms that implement automation gain a competitive advantage by enhancing efficiency, lowering operational costs and producing higher-quality products. This technological edge enables them to stay ahead in a rapidly evolving market. Sustainable practices, automation contributes to more sustainable aquaculture practices by minimizing environmental impacts and conserving resources (Yongqiang *et al.,* 2019). Future-proofing, as technology advances, automation continues to play a pivotal role in meeting the growing demand for seafood while addressing industry challenges.

8. Disadvantages of Automation in Aquaculture

High initial investment, automation systems often require a significant upfront investment in technology and infrastructure. Technical complexity, implementing and maintaining automation systems can be technically challenging and may require specialized knowledge and training. Dependence on technology, overreliance on automation can pose risks in case of system failures or technical glitches, potentially disrupting operations. Energy consumption, some automation systems, such as recirculating aquaculture systems (RAS), can have high energy demands, leading to increased operational costs (Wu *et al.,* 2022). Maintenance costs, automation systems require regular maintenance and occasional repairs, which can add to operational expenses. Compatibility issues, integrating different automation components and systems may face compatibility issues, requiring additional efforts for seamless operation.

9. Conclusion

The integration of robotics, AI and automation in aquaculture represents a transformative leap toward sustainable and efficient seafood production. By leveraging technologies such as underwater drones, smart sensors and data acquisition systems, robotics optimize feeding practices, monitor water quality and enhance disease detection, leading to healthier and more productive aquatic environments. These innovations reduce environmental impact by minimizing waste and resource usage while also improving operational efficiency. Additionally, advancements like underwater 3D printing for customized structures and autonomous vehicles for precise data collection drive further innovation. Biological models play a crucial role by helping us understand complex interactions between organisms and their environment, allowing for more efficient management strategies. Automation revolutionizes aquaculture by optimizing feeding, monitoring and harvesting, thus reducing labour and errors. As the demand for seafood grows, the adoption of these technologies ensures competitiveness, resilience and alignment with sustainability goals, positioning automation as the future of aquaculture and addressing global food security challenges.

10. References

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