EISSN 2602-473X

AQUATIC SCIENCES AND ENGINEERING

Aquat Sci Eng 2025; 40(1): 42-52 • DOI: https://doi.org/10.26650/ASE20241564766

Review

Building a Collaborative Aquaculture Research Ecosystem with APIs and AI

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Cite this article as: Sevin, S., & Dikel, S. (2025). Building a collaborative aquaculture research ecosystem with APIs and AI. *Aquatic Sciences and Engineering, 40(1)*, 42-52. DOI: https://doi.org/10.26650/ASE20241564766

ABSTRACT

Recently, the mission of the aquaculture production sector in achieving sustainable development goals has become increasingly critical. Synthesizing large data sets with advanced technological tools in aquaculture is no longer a luxury but a necessity for significant progress. This article examines the pivotal role of Application Programming Interface (API) integration in advancing open science and collaborative research in aquaculture. It also explores the use of Artificial Intelligence (AI) to facilitate data analysis across disparate databases and proposes the establishment of a ChatGPT-like virtual environment to catalyze seamless global collaboration among researchers. A comprehensive overview is presented on the feasibility of a unified AI-driven database that collects, analyzes, and shares data, overcomes geographical constraints, and supports a shared information ecosystem. The article scrutinizes current implementations, identifies gaps in existing infrastructures, and outlines a robust framework for API integration that could significantly enhance innovation and operational efficiency in aquaculture research.

Keywords: Artificial intelligence, Aquaculture, Application Programing Interface, Internet of things

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Submitted:
11.10.2024

Revision Requested:
14.11.2024

Last Revision Received:
20.11.2024

Accepted:
21.11.2024

Online Published:
17.01.2025

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INTRODUCTION

Every year, population growth, rising income levels, and increasing awareness of quality nutrition contribute to a significant rise in the demand for global food production. Aquaculture plays a critical role in meeting this demand. Consequently, the aquaculture industry has experienced remarkable growth in recent years. This growth is evident in the rapid increase in production, making it the fastest-growing sector in the global food industry, with an average annual growth rate of 6.9 percent over the past three decades (Ottinger et al., 2021). Furthermore, the industry's average annual growth rate from 1970 to 2005 was around 8.9%, significantly outpacing the growth rate of capture fisheries, which stood at only 1.2% (Abdul Kari et al., 2020). This growth has positioned aquaculture as the fastest-growing food-producing industry globally, driven by the increasing demand for food fish consumption (Pridgeon & Klesius, 2012). The expansion of the industry is also reflected in the development of aquaculture areas, with significant increases observed in regions such as China and Türkiye (Zhou et al., 2022; Erol, 2022; Wang et al., 2022). Additionally, the growth of the aquaculture industry has led to new trends, such as the increased production of hybrids in the aquaculture sector of some species, like grouper, due to improved growth and disease resistance compared to parent species (Nankervis et al., 2021).

However, this rapid development has not been without challenges. The accelerated growth of finfish aquaculture has resulted in developments detrimental to the environment and human health (Cabello, 2006). The industry's expansion has led to an increase in waste generation, raising concerns about environmental sustainability (Zhou et al., 2021).

Challenges such as preventing an increase in aquaculture production costs, the obligation to use resources rationally, waste management, and minimizing losses (even production with zero discharge) still maintain their significance. These challenges highlight the need for the industry to innovate toward low environmental impact systems to ensure sustainable growth (Gephart et al., 2020).

In the burgeoning field of aquaculture, technological innovation is not just a tool but a necessity to address the challenges of sustainability and efficiency. Aquaculture, a cornerstone of global food security, faces the dual challenge of meeting rising demand while maintaining ecological and economic sustainability. The industry's growth is intrinsically linked to its ability to innovate and adapt. In this pursuit, the seamless integration of Application Programming Interfaces (APIs) and Artificial Intelligence (AI) stands as a transformative force, offering new avenues for research and operational efficiency. The current landscape of aquaculture is characterized by fragmented data and knowledge systems. This fragmentation hinders the synthesis of multifaceted data ranging from environmental impacts to supply chain logistics, essential for informed decision-making and sustainable practices. There is a critical need for a paradigm shift towards open science—an ethos that promotes the accessibility, sharing, and collaborative use of research data and methodologies, fostering a culture of transparency and cooperative progress.

Artificial Intelligence in Aquaculture; Artificial Intelligence (AI) is transforming aquaculture by optimizing breeding programs, feed formulation, and disease treatment protocols. AI's ability to analyze large datasets allows for predictive analytics, which can improve operational efficiency and sustainability.

Internet of Things (IoT) in Aquaculture; The Internet of Things (IoT) connects various devices and sensors in aquaculture systems, enabling real-time monitoring of water quality, temperature, and other critical parameters. This connectivity enhances data collection and management, leading to better decision-making.

API Integration in Aquaculture; Application Programming Interfaces (APIs) facilitate seamless data exchange between different systems in aquaculture. By integrating APIs, researchers and practitioners can access and share data more efficiently, breaking down data silos and promoting collaborative research.

The integration of APIs and AI in this context is more than a mere technological enhancement; it is a strategic imperative. APIs facilitate the flow of information, breaking down the barriers of data silos, while AI offers advanced tools for interpreting complex datasets, driving insights that could revolutionize fish farming practices from breeding to health management and waste reduction. The integration of Application Programing Interfaces (APIs) and Artificial Intelligence (AI) offers a transformative approach to aquaculture research, fostering enhanced data sharing and collaborative efforts across global scientific communities.

The integration of artificial intelligence (AI) into the aquaculture sector has significant promise for revolutionizing efficiency, sustainability, and global food security. Leveraging AI technologies, such as machine learning and deep learning, in conjunction with modern information technologies, including the Internet of Things (IoT), big data, and cloud computing, has enabled aquaculture to optimize resource utilization and enhance long-term sustainability (Kaur et al., 2023). Furthermore, the application of AI in aquaculture systems has the potential to address critical water quality control challenges, thereby improving the overall efficiency of prawn harvesting from freshwater ponds (Kaur et al., 2023). Additionally, the utilization of AI-based systems for regulating key water quality factors, such as salinity, dissolved oxygen, pH, and temperature, demonstrates the transformative potential of AI in ensuring optimal aquaculture conditions (Kaur et al., 2023). Moreover, the incorporation of AI services using computer vision and deep learning recognition models in cloud-based autonomous drones has facilitated scalable and advanced aquaculture surveillance, further enhancing operational efficiency and sustainability (Ubina et al., 2021). These advancements underscore the pivotal role of AI in driving innovation and progress within the aquaculture sector, offering solutions to challenges and paving the way for sustainable and secure global food production.

Integrating AI technology can revolutionize aquaculture research by automating data collection and analysis processes. For example, AI systems can regulate key water quality factors such as salinity, dissolved oxygen, pH, and temperature, ensuring optimal conditions. This automation translates to significant time and cost savings, as it enables continuous and real-time monitoring, reducing the need for manual intervention. Furthermore, AI is transforming the development of intelligent fish farming systems by integrating with the Internet of Things (IoT) and big data technology. This integration facilitates the monitoring of aquaculture environments, leading to improved sustainability and productivity. Additionally, AI-driven advancements in aquaculture include the use of computer vision and deep learning models in cloud-based autonomous drones for scalable and advanced aquaculture surveillance, enhancing operational efficiency and sustainability. These examples illustrate how AI technology is reshaping aquaculture, offering efficient and cost-effective solutions that contribute to the industry's sustainable development.

Aquaculture's current state is marked by data silos and segmented research efforts, impeding the flow of information and hindering innovation. Collaborative efforts are often hampered by incompatible data formats and the lack of a centralized system for data management. This scenario underscores the need for a paradigm shift toward open science—an approach that advocates for the accessibility and sharing of research data and methodologies to foster collaboration and transparency.

Interoperability, that is, the ability of different information systems, devices, and applications to access, exchange, integrate, and cooperatively use data in a coordinated manner within and across organizational boundaries, is fundamental to actualizing open science in aquaculture. It promises to streamline research processes, reduce redundancies, and lead to more robust and rapid scientific discoveries. Aquaculture, with its diverse data sources ranging from satellite imagery to genomics, stands to gain enormous value from a framework that facilitates open science and interoperability. This section sets the stage for a discussion of how API and AI integration can catalyze this transformation.

This chapter lays the foundation for a discussion on how the fusion of API and AI technologies can catalyze a significant transformation within aquaculture, shifting the industry toward data-driven sustainable practices that can reshape not only the sector but also its relationship with the global ecosystem.

AI as a Data Analysis Catalyst

Artificial Intelligence (AI) in aquaculture is a game-changer for managing and interpreting the vast amounts of data generated by modern scientific methods. AI, through machine learning algorithms and data analytics, can identify patterns and insights that are beyond the scope of traditional data analysis methods.

AI methodologies suitable for aquaculture research range from neural networks for image recognition—useful for monitoring fish health and biomass—to machine learning models that can predict optimal feeding schedules. These AI-driven tools enhance the accuracy and efficiency of data analysis, leading to better informed aquaculture management decisions.

It also provides an overview of smart aquaculture systems, with a focus on machine learning and computer vision applications, demonstrating the potential of AI in interpreting complex aquaculture data and, in addition, AI-based data to minimize production costs and maximize fish production. The role of artificial intelligence innovation technology is very important in creating an intelligent cage culture management system containing modules (Chang,et al.,2021; Kaur,et al., 2023). Collectively, these references support the view that artificial intelligence, through machine learning algorithms and data analytics, will indeed be a game changer in managing and interpreting the large amounts of data generated by modern scientific methods in aquaculture research. The evidence presented in these studies underscores the transformative potential of AI in revolutionizing data analysis and decision-making in the aquaculture industry. The use of AI for predictive analytics allows real-time monitoring and forecasting of environmental conditions, disease outbreaks, and production outcomes. This foresight enables aquaculture practitioners to proactively manage risks and improve operational efficiency, ultimately leading to more sustainable practices.

ChatGPT-like Virtual Environment for Global Cooperation

To prepare a ChatGPT-like virtual environment for global collaboration in aquaculture, several important steps and considerations must be considered. Understanding the global potential of seafood farming is important for identifying regions with high potential for cooperation and collaboration. Gentry et al. (2017) highlighted the unknown global capacity for increased aquaculture production in the ocean and the relative productivity potential between countries. This study is important for mapping the global potential of marine aquaculture. Understanding the role of aquaculture in improving food security on a global scale is crucial for shaping collaborative efforts in aquaculture. Troell et al. (2014) highlighted the impact of aquaculture on global food security and resilience. Understanding the global potential of seafood farming is essential for identifying regions with high potential for cooperation and collaboration. Discussing the role of aquaculture in sustainable development and its potential to reduce poverty and improve food security on a global scale, Subasinghe et al. (2009) provided valuable insights into the broader implications of aquaculture for global collaborative efforts. Ottinger et al. (2018) stated that based on the significant contribution of aquaculture to global food security and protein intake, understanding the global importance of aquaculture is important for developing international cooperation in this field. Providing information on the Dual-Mode Underwater Smart Sensor Object for Precision Aquaculture Based on AIoT Technology, Chang et al. (2022) discussed the use of AIoT technology for precision aquaculture, highlighting the potential for integrating advanced technologies into aquaculture practices. Leveraging artificial intelligence and Internet of Things (IoT) technologies can improve global collaboration by facilitating data-driven decision making and information sharing. Aquaculture in China Presenting the current status, challenges, and outlook of industrial aquaculture, Li et al. (2011) provide insights into the current status of the aquaculture industry in China and its global implications. Understanding aquaculture experiences and challenges in different regions, such as China, can shed light on best practices and collaboration strategies on a global scale.

Referring to the Visual Aquaculture System Using Cloud-Based Autonomous Drones, Ubina et al. (2021) stated that combining computer vision and artificial intelligence services using cloud-based autonomous drones can improve aquaculture surveillance and monitoring. Applying advanced technologies to data collection and analysis can support global collaboration by providing real-time insights and information sharing.

Envisioning a ChatGPT-like virtual environment for the aquaculture research community requires a platform that uses natural language processing to understand and respond to researcher questions. This AI-driven environment will facilitate the exchange of ideas, data, and methodologies and collaborative efforts worldwide. The key features of such a platform include intuitive user interfaces, scalable infrastructure for processing large datasets, and customizable tools to suit various research needs. Real-time translation capabilities will further enhance the collaboration of researchers from different linguistic backgrounds. Implementing a virtual environment brings challenges such as ensuring data security, ensuring fair access, and preserving system integrity. Overcoming these obstacles requires careful planning, sound technical design, and ongoing community engagement to ensure the system meets the diverse needs of the aquaculture research community.

Building a Unified AI-Driven Database

Creating a unified AI-driven database for aquaculture research is an ambitious yet feasible goal. Such a database should integrate various forms of data, from genomic sequences to satellite imagery. The framework for this integration should be modular and flexible, allowing for the incorporation of new data types and sources as they become available.

Ensuring rigorous data entry and validation standards is essential for maintaining data quality. AI can play a significant role in this by using machine learning algorithms to detect and correct anomalies. Security and privacy are critical concerns, especially when handling proprietary or sensitive information. Therefore, encryption, access controls, and regular security audits should be integral components of the framework.

The potential of such a database is vast. By providing researchers with access to a rich, well-curated repository of data, it could accelerate discovery and foster collaboration on a scale previously unseen in aquaculture research.

In creating a unified AI-driven database for global collaboration in the field of aquaculture production, it is essential to consider the following steps and insights gained from the information provided. To enable autonomous data generation, a unified data representation and transformation method based on Adversarial generative network (GAN) models was designed (Zheng et al. 2023). In addition, a data integration system was utilized to provide users with access to distributed heterogeneous databases through a unified interface for information sharing (Lu et al., 2015).

To achieve explainable, robust, and general AI, human knowledge is integrated with data-driven machine learning (Zhuang et al., 2017), which involves combining data-driven models with structured models of logic rules and moving from task-oriented intelligence to artificial general intelligence in the general context.

Semantic Data Modelling follows the principles of Linked Data and uses the Resource Description Framework (RDF) data model to create a unified data model for description labels and visual features (Tran et al., 2022). Although the Resource Description Framework is a World Wide Web Consortium (W3C) specification designed as a metadata model, it is a general method used to model information in various syntax styles. This approach provides a standardized and interoperable representation of data for global collaboration.

A bidirectional architecture that integrates knowledge and data to create a framework for AI can be developed to promote independent learning and update knowledge and AI models (Deng et al., 2022)

By emphasizing the prevalence of data-driven artificial intelligence in autonomous and hybrid systems, such AI can be used for clinical decision support (Montani and Striani, 2019). This approach can be adopted to support decision-making in aquaculture production.

The Berlin Indexing and Harvesting Toolkit (B-HIT) can be used to collect web services and create a unified index database (Holetschek et al., 2019). This tool can facilitate the collection and organization of various data sources for collaboration with aquaculture applications.

Large amounts of data must be collected to create big data databases and use data mining to generate information (Li et al., 2023). This process is critical for extracting valuable insights and patterns from the combined database. By combining these steps and insights, a unified AI-driven database for aquaculture can be created to support global collaboration, knowledge sharing, and data-driven decision-making in aquaculture.

A unified database focused on artificial intelligence for global cooperation in the field of aquaculture can lead to several significant benefits. By integrating various technologies such as the Internet of Things (IoT), big data, cloud computing, and artificial intelligence, the database can facilitate sustainable aquaculture development (Ubina & Cheng, 2022). This integration can enable the real-time monitoring of aquaculture sites through computer vision, thus enhancing production and reducing labor while being environmentally friendly (Ubina et al., 2021; Vo et al., 2021). Furthermore, the use of artificial intelligence technologies, such as intelligent feeding techniques based on predicting shrimp growth, can improve water quality prediction and early warning systems, making aquaculture practices more accurate and efficient (Chen et al., 2022). Additionally, the application of modern technologies, including sensors, robots, drones, and artificial intelligence, can contribute to the development of aquaculture (Mustafa et al., 2021).

Global cooperation in the field of aquaculture, facilitated by a unified database, can address challenges such as the need for large amounts of labelled data to train artificial intelligence systems, which has been a bottleneck in further aquaculture applications (Yang et al., 2020). Moreover, the database can support the establishment of an aquaculture industry with world-class competitiveness, thereby contributing to sustainable development and seafood security (Chang et al., 2021). It can also help reduce the negative effects of aquaculture wastewater on global sustainability by identifying ways to apply modern technologies to existing aquaculture production methods (Han et al., 2019; Mustafa et al., 2021).

The benefits of a unified database focused on AI for global aquaculture cooperation align with the broader context of the application of AI in various fields. The framework for global cooperation on artificial intelligence and its governance aims to ensure that humanity can enjoy the benefits of artificial intelligence while minimizing its risks (Ala-Pietilä & Smuha, 2021). Furthermore, the use of AI technologies in aquaculture is part of the broader trend of applying modern technologies to improve production methods and sustainability in various sectors, including agriculture and fishery (Song, 2020; Subasinghe et al., 2009).

Concrete examples of how artificial intelligence-supported analysis can be used in aquaculture research are provided. "By deeply analyzing information from large data sets, AI can provide valuable insights into topics such as water quality, fish health, and feeding strategies. Feed efficiency plays a crucial role in aquaculture practices, particularly in industrial and offshore applications. Concepts such as the quantity, timing, and frequency of feed given to fish, as well as the decision to feed based on changing environmental conditions, are of vital importance in farm management. Achieving this management with minimal errors or, ideally, without any errors relies heavily on comprehensive observations and measurements. Instantaneous feeding of fish and subsequent adjustment of feed based on live weight gain are also essential. Typically, these values need to be continuously updated by engineers based on specific formulas and assumptions. Successful aquaculture processes depend on ensuring optimal fish feeding. Otherwise, fish may experience inadequate growth or overfeeding. One of the most effective ways to optimize this process is to manage operations by considering numerous assumptions with the assistance of artificial intelligence.

The integration of AI into the aquaculture sector represents a transformative leap that will propel scientific research and applications in this field to unprecedented levels. By harnessing AI, aquaculture can benefit from enhanced precision, efficiency, and sustainability. AI technologies enable the automation of critical processes such as data collection, analysis, and decision-making, leading to faster and more accurate results. This integration has the potential to revolutionize various aspects of aquaculture, including feed management, water quality control, disease detection, and growth monitoring. Moreover, the utilization of AI in aquaculture research extends to the development of intelligent fish farming systems by integrating IoT and big data technology to monitor aquaculture environments, leading to improved sustainability and productivity. The seamless integration of AI into aquaculture operations can significantly contribute to global food security by optimizing resource utilization, minimizing environmental impact, and enhancing the overall efficiency of food production. As the aquaculture industry continues to embrace AI-driven innovations, the future holds promise for sustainable and secure global food production, ensuring a steady supply of high-quality seafood to meet the demands of a growing population.

In conclusion, the creation of a unified database focused on artificial intelligence for global cooperation in the field of aquaculture can lead to numerous benefits, including enhanced monitoring, improved production efficiency, and sustainable development. This aligns with the broader trend of applying modern technologies, including artificial intelligence, to address challenges and improve practices in various industries.

Current Implementations and Gaps

An analysis of existing platforms reveals a landscape in which several initiatives have made strides toward unified data management; however, significant gaps remain. Current systems often suffer from issues like limited interoperability, inconsistent data standards, and inadequate user interfaces. These challenges lead to inefficiencies and barriers to entry that can discourage collaboration and slow innovation.

To bridge these gaps, it is crucial to identify and adopt best practices from successful implementations. This involves not only technological aspects such as the use of cloud-based storage and sophisticated data analytics tools but also the fostering of a culture that values data sharing and open science. Future developments must focus on creating more user-centric platforms that address the needs of researchers while maintaining high standards of data integrity and security.

To comprehend the current implementations and gaps in ChatGPT-like virtual environments for global collaboration, it is essential to consider the existing literature on virtual environments, global cooperation, and the use of virtual teams for collaboration. Virtual environments have been increasingly utilized for global cooperation, with studies emphasizing the potential to create global networks of employees and facilitate communication across international boundaries (Mueller et al., 2010). Additionally, the use of virtual teams has become prevalent due to the development of communication tools and the need to address the effectiveness of virtual teams (Shwartz-Asher & Ahituv, 2019). Furthermore, the potential for virtual team communication and cooperation in a virtual environment of computer technology has been highlighted (Kukytė, 2021).

In the context of global cooperation, it is crucial to consider the implications of virtual interactions and the potential for stimulating discussions that foster greater understanding and effective interaction in real-world collaborations (Lewis et al., 2010). Moreover, the promotion of cooperation among countries on global issues, such as climate change mitigation, has been observed in the context of initiatives like the Belt and Road Initiative (BRI) (Sultan et al., 2022). These references collectively underscore the growing significance of virtual environments and virtual teams in facilitating global cooperation and addressing transboundary concerns.

To understand the current practices and gaps in Collaborative Virtual Environments (CVEs) for global collaboration, it is crucial to consider the existing literature on virtual environments, global collaboration, and the use of virtual teams for collaboration. CVEs play a significant role in supporting collaborative work across distributed teams by providing a common virtual space for real-time interaction and manipulation of virtual artifacts (Cunha et al., 2008). These environments are particularly relevant for global virtual teams working across geographical and cultural boundaries (Larsson, 2003). In the context of open science data platforms in different countries, the success and areas that require improvement can be analyzed by looking at platforms like the Global Nutrition and Health Atlas (GNHA) and the European Open Science Cloud (EOSC). The GNHA serves as an interactive tool for sharing information, fostering collaborations, and driving innovation (Zhou et al., 2022). On the other hand, data platform providers often struggle to aggregate data to meet user needs and establish high-intensity data exchange in collaborative environments (Laufs et al., 2022). This highlights the need for improved data aggregation and exchange mechanisms in open science data platforms to enhance collaboration and knowledge sharing. Moreover, the emergence of platforms like the EOSC, provides researchers and professionals with a virtual environment in which to store, share, and reuse large volumes of information generated by the big data revolution (Kaivo-oja & Stenvall, 2022). Such platforms offer new interaction styles and sharing approaches that can lead to novel results and regulations, including data and analysis platforms, scientific social networks, and new forms of collaboration (Kondoro et al., 2017). In conclusion, leveraging Collaborative Virtual Environments and open science data platforms can significantly enhance global collaboration by providing shared virtual spaces for real-time interaction and facilitating data sharing and knowledge exchange. However, there is a need to address challenges related to data aggregation, user needs alignment, and efficient data exchange mechanisms to further improve collaboration among global teams in virtual environments.

However, as virtual environments continue to evolve, emerging challenges and gaps must be addressed. For instance, the shift toward real-time voice and photorealistic digital personas in virtual systems like ChatGPT raises concerns about the potential threats posed by conversational AI as a vector for targeted influence (Rosenberg, 2023). Additionally, the effectiveness of virtual teams and the antecedents of virtual team effectiveness remain areas that require further empirical research to bridge existing gaps (Shwartz-Asher & Ahituv, 2019). Furthermore, the need to disclose and address issues such as the formation of clusters in virtual reality, the development of network relationships, and cooperation in the global digital space has been highlighted as areas requiring further exploration (Kraus et al., 2021).

The current literature reflects the increasing utilization of virtual environments and virtual teams for global cooperation while also highlighting emerging challenges and gaps that must be addressed. As technologies like ChatGPT continue to advance, it is essential to consider the potential implications for global cooperation and address the evolving needs and challenges of virtual collaboration.

Framework for Robust API Integrations

To galvanize the aquaculture research community toward unprecedented levels of collaboration, a robust framework for API integration is indispensable. Such a framework must prioritize scalability to ensure that APIs can handle increasing loads and complexity as the community grows. Efficiency must be engineered into the system to minimize latency and maximize response times, while user-friendliness is paramount to encourage widespread adoption by researchers with varying levels of technical expertise.

From a technical perspective, the proposed framework should adopt a microservices architecture that allows independent scaling and iterative development. Containerization technologies like Docker and Kubernetes are pivotal for deployment and management. Organizational considerations include the establishment of cross-functional teams comprising developers and end users to ensure that the APIs are aligned with researcher needs.

Policy implications are vast and critical. There must be a concerted effort toward standardization to ensure that APIs can communicate effectively across diverse systems. Initiatives such as the OpenAPI Specification can provide a foundation to create consistent and standard API descriptions, which are vital for interoperability.

In addition, security protocols must be embedded into the API design to safeguard sensitive data. OAuth (Open Authorization) and other authorization frameworks can ensure that data access is controlled and that user permissions are managed appropriately. It is also essential to consider the implications of data sovereignty and the regulations that govern data transfer across borders, which may impact the architecture of a global research platform.

To promote widespread adoption, policies should encourage open standards and provide clear guidelines for API documentation and versioning. This ensures that as APIs evolve, researchers can adapt without losing access to vital data and functionality. The integration framework should also foster an environment that supports the development and sharing of API-related tools and best practices.

Implementing such a framework requires a balance between innovation and regulation, necessitating collaboration between technologists, researchers, and policymakers. By building consensus on standards, the aquaculture research community can create a resilient API ecosystem that promotes the science and practice of aquaculture.

To develop a solid framework for API integrations in the aquaculture industry, it is important to consider the following aspects and insights: First; It is necessary to ensure compliance with state-of-the-art API policies. Best practices that facilitate scalability and robustness in this regard can be found in Rodríguez et al. (2016). Subsequently, the aquaculture industry can achieve increased environmental, economic, and social acceptability and contribute to sustainability by adopting integrated polytrophic practices (Chopin et al., 2001) . In support of this issue, the integration of monitoring methods combined with the Internet of Things (IoT) and Internet+ frameworks has been proposed as robust tools for tactical decision-based management in marine farming and aquaculture (Zhou et al. al., 2019) . The framework must include tools and practices for responsible AI engineering to ensure robustness, scalability, and ethical considerations in API development (Soklaski et al., 2022). Extending the framework to integrate nature-based solutions and marine spatial planning could identify opportunities to increase food production and reduce environmental damage in the aquaculture sector (Hughes, 2021). The framework should emphasize interoperability and the use of standards-based smart city data platforms to ensure seamless integration of various aquaculture data sources (Jeong et al., 2020). The framework should address occupational safety and health standards, including best practices and capabilities to ensure worker safety in the aquaculture industry (Fry et al., 2019). An ecosystem-based framework can provide a structured methodology for assessing the impacts of aquaculture and integrating best management practices (Cranford et al., 2012). The framework should include APIs to process environmental images and integrate time series data with modeling systems to realize comprehensive data analysis and decision making (Mac Coombea et al.,2017). A multi-layered system robustness testing strategy based on abnormal parameters and fault injection can ensure the robustness of the API framework (Xiang et al., 2013). By integrating these considerations into a comprehensive framework, a robust and scalable API integration system can be established for the aquaculture industry to support sustainability, environmental responsibility, and operational efficiency.

To optimize an API gateway using Docker and Kubernetes, organizations can leverage microservices and container technologies to enhance data flow in the API architecture. By breaking down the monolithic structure into smaller, independent services, greater flexibility, scalability, and efficiency in managing API requests and responses can be achieved. The following studies are presented as examples of work done on this topic.

a. Containerization with Docker: Docker can be used to containerize microservices within the API gateway. Docker containers encapsulate each service and its dependencies, ensuring consistency across different environments (Li et al, 2021). - Docker containers allow developers to package applications and their dependencies into standardized units, providing a lightweight and portable solution for deploying microservices (Malić et al., 2019).

b. Microservice architecture: Implementing a microservice architecture involves designing each service as an independent, self-contained unit responsible for a specific business capability (Li et al., 2021). - Microservices promote loose coupling, allowing for independent development, deployment, and scaling of services, which aligns well with the principles of containerization (Dragoni et al., 2017).

c. Orchestration with Kubernetes: Deploying Docker containers containing microservices on a Kubernetes cluster allows for efficient orchestration and management of services (Saboor et al., 2022). Kubernetes automates the deployment, scaling, and management of containerized applications, ensuring high availability and optimal resource utilization (Chandrasekaran et al., 2022).

d. API gateway optimization: Kubernetes can be used to scale the API gateway horizontally by adding more instances of the gateway to handle increased traffic and improve performance (Muzumdar, 2024). - Kubernetes provides features like service discovery and load balancing, which are essential for optimizing the API gateway and ensuring seamless communication between microservices (Muzumdar, 2024).

e. (CI/CD): Implementing CI/CD pipelines automates the testing, building, and deployment of microservices within the API gateway (Donca et al., 2022). - CI/CD practices help maintain the quality of services, accelerate the release cycle, and ensure smooth integration of new features into the API architecture (Donca et al., 2022). By combining Docker for containerization, Kubernetes for orchestration, and a microservice architecture, organizations can streamline data flow in the API architecture. These technologies enable efficient service management, enhanced scalability, and improved overall performance of the API gateway, leading to a more robust and agile system for handling API requests and responses.

Future of Aquaculture Research with API and AI Integration

Long-term Impacts of Technological Integration

The integration of APIs and AI into aquaculture research is expected to have profound and far-reaching consequences. Enabling seamless data sharing and sophisticated analysis will accelerate the pace of discovery, leading to more rapid advancements in sustainable aquaculture practices. In the long term, AI can automate and optimize breeding programs, feed formulation, and disease treatment protocols, enhancing yields and improving the overall health of aquaculture stocks (Arcelay et al.,2021; Jogdand, 2024). Moreover, the predictive power of AI could lead to better anticipation of environmental impacts and market demands, ensuring the resilience of aquaculture systems against the uncertainties of climate change and economic fluctuations.

Furthermore, the long-term effects of technological integration in aquaculture research are expected to extend to workforce development and skill requirements. AI and API technologies will become integral to aquaculture operations, and the demand for a competent workforce with expertise in AI-driven aquaculture management is likely to increase. This necessitates a strategic approach to identify and address future skills needs in the aquaculture sector, aligning with the evolving technological landscape (Arcelay et al., 2021). The ethical implications of AI and API integration in aquaculture research are also paramount. The responsible and ethical use of AI technologies, coupled with robust API integrations, will be critical in ensuring patient-centered care, environmental sustainability, and worker safety within the aquaculture industry (Ayling & Chapman, 2021; Watterson et al., 2020). Additionally, the future of aquaculture research with AI and API integration is expected to benefit from academia-industry collaboration, as highlighted in the context of software engineering education. The instrumental role of AI in shaping the trajectory of aquaculture research and industry practices underscores the potential for synergistic partnerships between academia and industry to drive innovation and knowledge creation (Wang, 2023).

To provide an example to better understand the Future of Aquaculture Research with API and Artificial Intelligence Integration, the use of real-time monitoring and diagnosis systems using computer vision on artificial intelligence-supported disease detection systems in aquaculture can be examined. Malik et al. (2017) proposed an automated fish identification model based on image processing techniques. Their study specifically addressed Epizootic Ulcerative Syndrome (EUS), a disease caused by a fungal pathogen that is often mistaken for ulcers by observers. The researchers employed a series of image processing methods, starting with histogram equalization for image segmentation and then Canny edge detection. They utilized two feature descriptor techniques, namely Histogram of Oriented Gradients (HOG) and features from an acceleration segment test (FAST), to extract pertinent image features. Classification tasks were then conducted using two types of neural networks alongside the K-Nearest Neighbors (K-NN) algorithm (Mia et al.2022). The steps taken to automatically recognize fish disease are shown in Figure 1.

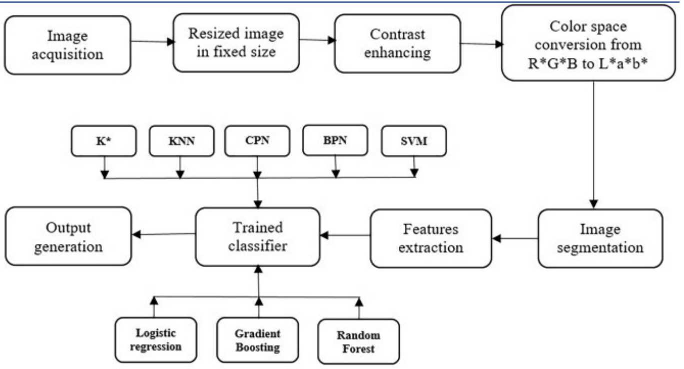

Figure 1. The working process of an automatic fish disease recognition system (Mia et al.2022).

Challenges and Solutions

The widespread adoption of APIs and AI is not without challenges. A major concern is data privacy and security. As aquaculture databases become increasingly interconnected, sensitive information could be at risk of breach. Ensuring robust cybersecurity measures and establishing clear data governance policies are essential. In addition, there may be resistance to adopting new technologies due to the cost of implementation and the need for technical expertise. To address these challenges, aquaculture communities should focus on developing user-friendly platforms and providing comprehensive training programs. It is also important to advocate for scalable solutions that can be adapted to various operational scales, from small-scale farms to large commercial enterprises.

Another challenge is the potential for data homogenization, which might overlook localized or context-specific knowledge that is crucial for certain aquaculture systems. To address this need, AI systems should be designed to be adaptable and learn from diverse data sources, including indigenous and local knowledge systems, to ensure that the insights generated are nuanced and applicable across different contexts.

To address the challenges and solutions related to the integration of APIs and AI into aquaculture, it is essential to consider the multifaceted nature of aquaculture and the potential benefits of integrating AI technologies. The challenges of AI integration with big data have been discussed in various studies (Dwivedi et al., 2021). Among Aquaculture 4.0 technologies, AI is receiving increasing attention, indicating its potential relevance in addressing aquaculture challenges (Mustafa et al., 2021).

In the aquaculture context, the challenges and solutions related to AI integration can be further understood by considering the broader applications of AI in various domains. For instance, in radiology, aspects such as system integration, vendor compatibility, and the availability of vendor-neutral solutions are crucial considerations when implementing AI (Adams et al., 2020). In addition, data quality is a critical factor that influences the implementation of AI applications (Lu et al., 2022). The potential benefits of integrating AI into existing workflows, such as enhanced automation and the utilization of feedback for further improvement, have been highlighted in the context of radiology (Dikici et al., 2020). Moreover, the challenges faced by developers when recommending APIs include mashup-oriented APIs, time-consuming processes, and limited usage of code (Nawaz et al., 2022).

In summary, the integration of APIs and AIs into aquaculture presents both challenges and opportunities. Leveraging AI technologies, such as IMTA and Aquaculture 4.0, can contribute to more sustainable and efficient aquaculture practices. However, challenges related to data quality, system integration, and developer considerations must be addressed to realize the full potential of AI integration in aquaculture.

Cultivating an International Collaborative Community

Fostering a global community centered on open science and collaboration requires concerted efforts from multiple stakeholders. International consortia could be established to set common goals, share best practices, and coordinate research efforts. Such consortia would also play a key role in standardizing APIs and AI applications in aquaculture to ensure compatibility and interoperability across different systems.

Encouraging open access to research findings and datasets is another strategic way to enhance collaboration. This could be facilitated through incentives for researchers who publish in open-access journals or contribute to shared databases. Additionally, global conferences and symposia dedicated to API and AI in aquaculture provide platforms for knowledge exchange and networking.

The integration of artificial intelligence (AI) and application programing interfaces (APIs) in aquaculture has the potential to foster the development of an internationally cooperative community. Technological advancements in AI and API integration offer opportunities for collaboration, knowledge sharing, and sustainable development within the aquaculture industry. As the aquaculture sector continues to embrace AI and API integration, considering the multifaceted implications and potential long-term effects of this technological convergence is essential.

The challenges and solutions in aquaculture research with AI and API integration are multifaceted and encompass various aspects, including data management, ethical considerations, security, workforce development, environmental sustainability, and technological limitations. Addressing these challenges requires advanced data management tools, ethical frameworks, cybersecurity measures, training initiatives, sustainable practices, and technological advancements.

The potential for international cooperation in aquaculture research through AI and API integration is evident in the growing body of literature that emphasizes the global significance of aquaculture production and the need for sustainable development. The rapid growth in aquaculture production, the expansion of the aquaculture industry worldwide, and the increasing demand for aquatic products underscore the importance of international cooperation and collaboration to address the challenges and leverage the opportunities presented by AI and API integration in aquaculture.

The references provided offer valuable insights into the global status and trends of aquaculture, the impact of aquaculture on fish supplies, the role of beneficial bacteria in aquaculture, and the potential for sustainable development in marine finfish aquaculture. These references contribute to our understanding of the challenges and opportunities associated with AI and API integration in aquaculture and provide a foundation for fostering international cooperation in the industry.

Thus, the integration of AI and APIs into aquaculture research presents an opportunity to develop an internationally cooperative community that promotes sustainable development, knowledge exchange, and collaborative efforts to address challenges and opportunities in the aquaculture industry.

CONCLUSION

As we navigate the currents of innovation, the integration of Application Programming Interfaces (APIs) and Artificial Intelligence (AI) stands as a beacon for the future of aquaculture research. The explorations within the preceding chapters have charted a course towards a more interconnected, efficient, and collaborative research environment, underpinned by these technologies.

The transformative potential of API and AI integration in aquaculture research cannot be overstated. APIs promise a new era of collaboration, where data flows freely across institutional and geographic boundaries, empowering researchers to build upon each other's work. AI offers the tools to make sense of the deluge of data, providing insights that drive sustainability and productivity in aquaculture practices.

This paper serves as a clarion call to action for the aquaculture research community. Researchers are urged to champion the adoption of open science principles, technologists to develop more advanced and accessible platforms, and policymakers to create frameworks that nurture this technological growth while safeguarding data privacy and integrity. The collective efforts of these stakeholders are critical in realizing the vision of a technologically empowered aquaculture research community.

Looking ahead, the landscape of aquaculture research is set to be reshaped by the adoption of the proposed technological solutions. The integration of APIs and AI represents more than just an enhancement of research capabilities; it signifies a transformative step towards a future where the aquaculture sector thrives on innovation, data-driven decisions, and a global network of shared knowledge. Future research should focus on developing scalable AI models, improving data interoperability, and fostering international collaboration through open science initiatives. These efforts will ensure sustainable practices, enhanced fish health and yields, and better environmental management. The potential benefits are immense, including more sustainable practices, enhanced fish health and yields, and better environmental management. Yet, the true success of this integration will be measured not only in scientific advances but also in how it fosters a collaborative culture that embraces transparency and inclusivity. As we cast our nets wider to the possibilities of tomorrow, let us also anchor our endeavours in the collaborative spirit that API and AI integration inherently promotes. It is through the shared pursuit of knowledge and the collective wisdom of the aquaculture community that we can ensure a bountiful and sustainable future for both the industry and the ecosystems it depends upon.

In conclusion, we advocate the integration of Kubernetes and AI technologies to enhance the scalability and efficiency of aquaculture research. Citing successful implementations like those at the Broad Institute and NOAA, we underscore the potential for these technologies to transform aquaculture research practices to become more sustainable and productive.

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