DEVELOPMENTS IN AQUACULTURE:

Trends, Challenges, and Applications

1st Edition

Editor

Prof. Dr. Yusuf BOZKURT

GLOBAL ACADEMY

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Developments in Aquaculture: Trends, Challenges, and Applications –Ist Edition–

Editor

Prof. Dr. Yusuf BOZKURT

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PREFACE

Aquaculture is playing an increasingly critical role in global food security and sustainable development. While advances in technology, biotechnology, and data science offer great opportunities for the aquaculture sector, there is also a growing need for new approaches to ensure environmental, economic, and social sustainability.

This book, *"Developments in Aquaculture: Trends, Challenges, and Applications – Ist Edition"*, provides a broad overview of current issues and recent developments in aquaculture. It covers a wide range of topics including new technologies, sustainable feed alternatives, monitoring methods, genetic biomarkers, and digitalization.

The book includes eight original chapters, each focusing on different aspects of aquaculture. It is designed to help researchers and industry professionals better understand today's trends, challenges, and practical solutions in the field. With both theory and practical examples, it supports readers in building knowledge and creating new approaches in the sector.

We would like to thank all the contributing authors and Global Academy Publishing for their efforts. We hope that this work will make a valuable contribution to aquaculture science and its practical applications.

Editor

Prof. Dr. Yusuf BOZKURT

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CONTENTS

CHAPTER I

TECHNOLOGICAL ADVANCEMENT IN AQUACULTURE

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Introduction

Aquaculture is one of the fastest-growing food sectors in agriculture globally (FAO, 2020; Ahmed, Thompson & Glaser, 2019). It is the practice of cultivating and producing aquatic organisms, including finfish and shellfish, for food and non-food purposes. Most aquaculture production takes place in controlled or semi-controlled systems. Aquaculture is rapidly emerging as a sustainable alternative to commercial fishing, helping to reduce pressure on wild fish stocks (Grealis et al., 2017). About 88% of global aquaculture production is consumed directly by humans, emphasizing the industry's critical role in global food security (Yang, Ramezani, Utne, Mosleh & Lader, 2020). With the increase in global population, aquaculture production must significantly expand to meet the increasing demand for fish. A three-fold increase in the next decade would require major advancements in sustainable feed sources, water quality management, and disease control (O'Neill, Stejskal, Clifford & Rowan, 2020; Yang et al., 2021a). China has dominated global aquaculture production with 55.65 million tons of total aquaculture output, according to 79% of the country's total fish production. Additionally, the annual per capita consumption of aquaculture products in China is 37 kg, twice the world's average according to 2020 data (Action, 2020). Aquaculture plays a significant role in reducing poverty (Ahmed, Thompson & Glaser, 2019), enhancing income (Grealis et al., 2017), employment (FAO, 2020), economic growth, and increasing the nutrition of the population (Genschick, Kaminski, As & Cole, 2017).

Growing global production, rising incomes, and greater awareness of the health benefits of protein consumption have significantly increased the demand for global food production, particularly protein sources. Fish and fisheries products are incredibly nutritious, offering high-quality protein that is easily digestible and rich in essential amino acids, especially long-chain polyunsaturated fatty acids (LCPUFA) (Ahmad, Ahmed, Fatma & Peres, 2021; Ahmad, Aurpa, & Azad, 2022). Additionally, fish is an excellent source of micronutrients like iodine, selenium, vitamin D, and various B vitamins (Beveridge et al., 2013). The Food and Agriculture Organization (FAO) states that fish is crucial to global food security. More than a billion people worldwide rely on fish as a primary source of animal protein, especially in developing countries and coastal regions (FAO, 2020).

Effective fisheries management is essential for sustainable fish populations, enforcing regulations, protecting marine and aquatic biodiversity, maintaining ecosystem balance and economic viability of fishing industries, and safeguarding livelihoods (Szuwalski, Burgess, Costello & Gaines, 2017). It depends on reliable and accessible data. Informed decision-making in fisheries management depends on key factors like fish stocks, catch rates, fishing methods, and environmental impacts (Dennis, Plaganyi, Van Putten, Hutton & Pascoe, 2015). Data allows regulators to track the health of fish populations, adjust quotas, enforce regulations, and protect marine ecosystems. Moreover, it fosters transparency and accountability, which are critical for balancing the economic needs of fishing communities with the long-term sustainability of marine resources (Beddington et al., 2007).

Fishery management is increasingly embracing holistic, ecosystem-based approaches, which consider the health of target species and the broader environmental and human factors that affect marine ecosystems (Pedreschi et al., 2019; Link & Marshak, 2022). The rapid development of digital technology has revolutionized industries by eliminating the need for manual tasks, automatic repeating processes, and improving efficiencies. The development of fishery production relies on the deep integration of modern digital technology like the Internet of Things (IoT), artificial intelligence (AI), blockchain, and cloud computing (Malde et al., 2020; Rubbens et al., 2023). These technologies are revolutionizing aquaculture by improving efficiency, productivity, and sustainability (Figure 1). These devices use sensors and internet connectivity to gather data about their surroundings and can transmit this information without the direct need for human interaction (AWS; TechTarget; Mattern & Floerkemeier, 2010; Clark, 2016). This review article aims to provide an overview of the possible contributions of digital technologies in fisheries and aquaculture, highlighting key developments, emerging trends, challenges, and innovative applications to the advantage of sustainable fisheries management.

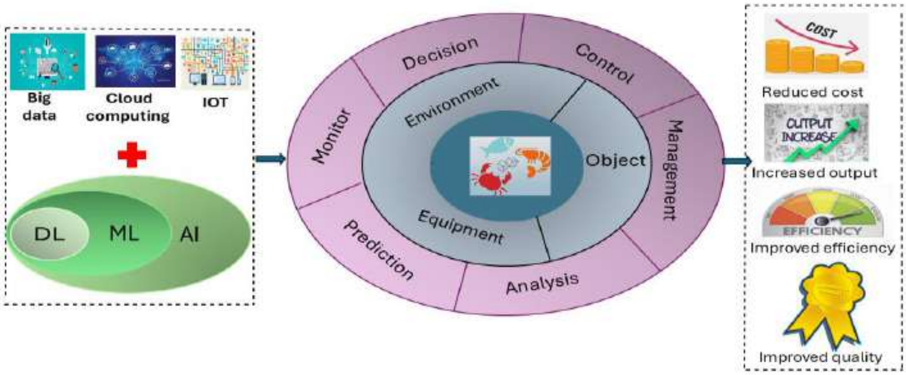

Figure 1. Emerging technologies for revolutionizing aquaculture by improving efficiency, productivity, and sustainability (Yang et al., 2021b)

Developments and Trends

a. *Blockchain Technology*

Blockchain has significant potential in fisheries management and offers a revolutionary way to create transparent and traceable supply chains, ensuring the sustainability, authenticity, and provenance of seafood products. Here are some key benefits of blockchain in aquaculture:

Traceability

Blockchain technology offers transformative potential for the seafood supply chain. It offers a record of the product journey from capture to the consumer's place. Every transaction from harvesting and processing to distribution ensures that all stakeholders have a reliable history of seafood products. Consumers can verify the origin and handling of seafood. It reduces the risks of mislabeling and illegal fishing practices. It builds confidence in the sustainability and safety of seafood products. Blockchain technology gives unique codes to fisheries to enhance data sharing and traceability (Ravishankar et al., 2021; Figure 2).

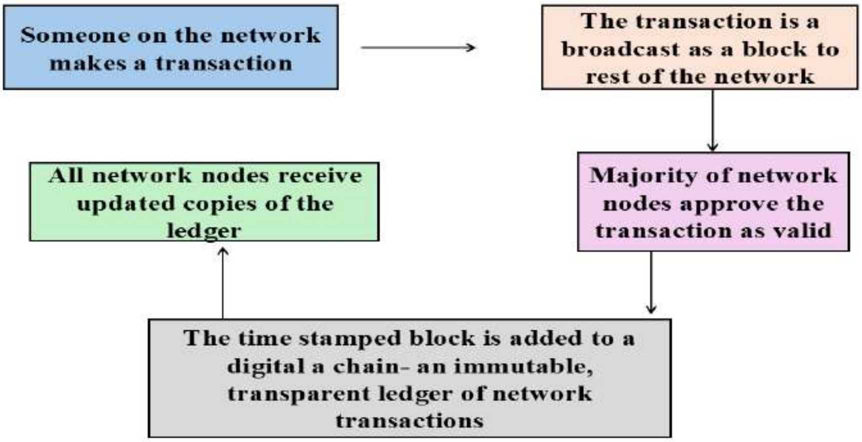

Figure 2. A typical blockchain transaction Mechanism (Howson, 2020; Bhanja et al., 2024)

Combating Illegal Fishing and Marine Conservation

Illegal, unregulated (IUU), and unreported fishing poses a severe threat to marine ecosystems and global food security. Blockchain technology offers a powerful solution for combating illegal and unregulated fishing by creating tamper-proof records of fishing activities, traceability across the food chain, real-time monitoring, detecting illegal activities, building trust among stakeholders, and promoting sustainable fishing practices. In 2017, the seafood industry explored the use of blockchain technology to improve transparency, traceability of fish products, and sustainability in supply chains (Girard & Payrat, 2017). It helps to verify the origin and legality of fish products to protect marine ecosystems.

Quality Assurance

Blockchain technology provides information about safety, quality, and freshness of fish food products. This traceability allows companies to quickly address any contamination and spoilage and allows them to improve overall food safety management if necessary (Nagajothi & Khanna, 2023).

Certifications and Compliance

Certifications like ASC (Aquaculture Stewardship Council) and MSC (Marine Stewardship Council) are integrated effectively into blockchain technology to provide transparent and verifiable proof of responsible and sustainable fishing practices (Nagajothi & Khanna, 2023).

Resource Monitoring and Management

Blockchain technology can provide a secure and transparent system for tracking and verifying real-time data from IoT devices and sensors. In aquaculture, this can revolutionize how data on fish stocks, fishing activities, and environmental conditions are monitored, shared, and collected. The Blockchain system records this data securely, helps the authorities to check fishing activities, enforce regulations, makes data-driven decisions, and promotes long-term sustainability in aquaculture.

b. *Artificial Intelligence*

Artificial intelligence offers immense potential for revolutionizing aquaculture by providing data-driven insights, optimizing resource allocation, fish growth optimization, health status monitoring, and promoting sustainability (Cheng, Zhang, Chen & Wang, 2023; Figure 3).

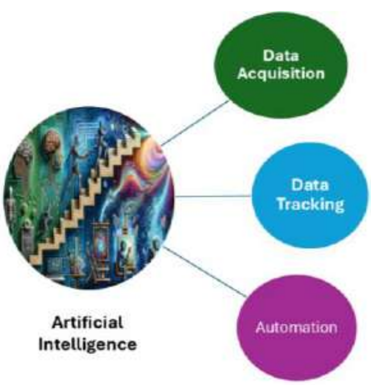

Figure 3. The integration of AI within various digitalization endeavors (Fernandes-Salvador et al., 2022; Mohale et al., 2024)

Here are some ways AI can be applied in aquaculture and fisheries management:

Automatic Feeding System

AI devices release precise amounts of feed at scheduled intervals, ensuring fish consume the right amount without wastage and overfeeding (Rawat, 2022). AI can analyze the fish size, species, temperature, and feeding behavior by improving the feed conversion ratio to determine the ideal feeding. AI enhances the aquaculture system more sustainably with optimized feeding, better growth, reduced stress, and appetite in fish, contributing to higher yields (Lloyd, Jothiswaran, Velumani, Agnes & Jayaraman, 2020; Rather et al., 2024).

Sex Determination and Breeding

In image-based sex determination, large databases of fish images are used in AI systems to recognize the large differences in morphology or coloration to distinguish between males and females. AI analyzes genetic patterns, shapes, and colors to identify sex-specific characteristics and accurate sex determination, reducing the need for manual examination (Rather et al., 2024). AI significantly increases efficiency and precision across various fields, including fisheries management, trading, and aquaculture, to achieve desired traits by automating complex tasks and improving decision-making (Mandal & Ghosh, 2023). AI is revolutionizing fish production by analyzing extensive genomic data to identify the genetic variations linked to specific characteristics. This enables the creation of performance prediction models, optimizing breeding programs, and improving production efficiency (Dixit Kumar, Srinivasan, Vincent & Krishnan, 2023). Fish productivity and spawning are highly dependent on temperature. The AI system adjusts the water temperature conditions to optimal levels, significantly improving the fish population productivity, reproduction, and sustainability. This innovative approach benefits aquaculture and contributes to more effective fisheries management practices (Mandal & Ghosh, 2023).

Fish Seed Screening

Fish seed quality is a critical factor in successful fish farming operations. Healthy fish seed ensures optimal growth rates, reduces mortality, is labor intensive, and improves overall productivity. The integration of advanced technologies like Microsoft Azure Machine Learning Studio and AI for sorting fingerlings efficiently was introduced by Kindai University in 2019 (Microsoft Asia News Center, 2019). By automating the identification and removal of irregularly shaped and unhealthy fish seeds, such systems reduce labor intensity and optimize overall efficiency. Additionally, this approach minimizes human error and ensures more consistent quality in fish seed selection. (Lloyd, Jothiswaran, Velumani, Agnes & Jayaraman, 2020).

Behavioral Analysis

Real-time behavioral observation has undergone significant advancements when paired with cameras in controlled and natural settings, allowing researchers to gather and analyze individual behavioral data immediately (Chang et al., 2021). This capability is critical for identifying early signs of environmental risks and facilitates the acquisition of live individual behavioral data from cameras in various fields. Advanced image processing can analyze the subtle changes in fish behavior, swimming patterns, and physical appearance that indicate stress, disease, and environmental changes (Nasrin, 2024).

Fish Growth, Health Monitoring, and Disease Detection

Traditional methods like manual measurements or visual inspections are inefficient for large fish populations due to the lack of real-time accuracy, the propensity for human error, and the critical need for assessing growth and health in fish populations (Kumar, Ganesh, Turukmane, Batta & Sayyadliyakat, 2022). Advanced monitoring techniques like imaging systems, automated sensors, and non-invasive biometrics, have revolutionized aquaculture by providing precise and accurate measurements for assessing fish health, growth, and environmental conditions (Gladju, Kamalam & Kanagaraj, 2022).

AI is transforming the aquaculture industry by using sensor and camera data to detect early signs of stress, disease, and illness in fish. Cameras are used to identify the behavioral patterns related to decreased activity, abnormal swimming patterns, and changes in fish feeding behavior (Rather et al. 2024). AI is revolutionizing the aquaculture industry by enabling early disease detection, and treatment, reducing the risks of outbreaks, and promoting more sustainable practices (Li et al., 2023). AI analyzes the images and videos from farm cameras to detect symptoms like unusual behavior, discoloration, and fish body lesions (Yang et al., 2021b; Chan, Fan & Yao, 2022). It enables the farmers to make informed decisions about treatment and prevention and reduces the risk of outbreaks and antibiotic use, thus improving overall productivity. It enables aqua culturists for early detection of fish infections, minimizes fish losses, prevents epidemics, and preserves the stock and yield of fish (Rather et al., 2024).

Epizootic ulcerative syndrome (EUS) is a widespread disease affecting fish populations and causes fish mortality in various countries such as India, the UK, Japan, Thailand, Pakistan, and Australia. To combat EUS, researchers employ advanced data analysis techniques including Neural Network Algorithm (ANN), Principal Component Analysis (PCA), and Visual Exploratory Disease Analysis (VEDA) (Malik, Kumar & Sahoo, 2017). Time-series analysis is a powerful approach for predicting future disease outbreaks by analyzing past health data by using methods like RNNs, LSTM, and ARIMA (Kumar, Ganesh, Turukmane, Batta & Sayyadliyakat, 2022).

Environmental Monitoring, Management, and Conservation

The integration of smart sensors in aquaculture has revolutionized environmental monitoring and management. These advanced tools provide real-time, precise measurements of critical water quality parameters like ammonia, dissolved oxygen, salinity, pH, and temperature (Nasrin, 2024). The real-time data generated by advanced monitoring systems empowers aquaculture operations with comprehensive insights into the aquatic environment. This facilitates immediate decision-making to address potential challenges. Artificial driver analysis extends beyond basic monitoring, offering valuable insights into dynamic changes within the ecosystem and identifying potential threats. These innovations collectively enhance the resilience and sustainability of aquatic ecosystems, promoting long-term productivity and environmental balance (Capetillo-Contreras, Pérez-Reynoso, Zamora-Antuñano, Álvarez Alvarado & Rodríguez-Reséndiz, 2024). AI-based water quality monitoring systems have revolutionized how we detect and address potential water quality issues (Zhang & You, 2024). By employing advanced algorithms, these systems can identify patterns and anomalies in water parameters signaling potential issues before they escalate. This allows for proactive interventions, minimizing the impact on aquatic ecosystems and public health (Javaid, Haleem, Khan & Suman, 2023).

Fish Genetics and Biotechnology

AI has emerged as a powerful tool for conservation efforts, particularly for endangered fish species. By analyzing genetic data, AI enhances understanding of genetic diversity, enabling the identification of critical genetic variations and patterns (Rather et al. 2024). Machine learning algorithms efficiently process vast amounts of genetic information, genetic bottleneck effect, and inbreeding risks. By integrating AI into conservation practices, decision-making becomes more efficient and effective, ultimately contributing to the long-term survival of endangered fish species and the ecosystem they inhabit (Vilhekar & Rawekar, 2024). AI has become an indispensable tool in aquaculture and fisheries research, especially in the field of genetics. By identifying a genetic marker associated with critical traits such as disease resistance, reproduction, growth performance, and environmental adaptability, AI contributes significantly to species survival and conservation (Palaiokostas, 2021). The ability of AI to analyze vast genomic datasets with precision and accuracy enhances the efficiency of sequencing technologies, offering researchers deep insight into genetic diversity, evolutionary pathways, and functional attributes of fish populations. This capability is essential for developing sustainable aquaculture practices, improving breeding programs, and mitigating the impacts of environmental stressors (De Alwis et al., 2022).

Fishing Activities Monitoring

Tracking the footprint of fishing vessels is crucial for ecological preservation and sustainable marine fisheries management. Advancements in information technology have introduced systems like Vessel Monitoring Systems (VMS), and Automatic Identification Systems (AIS), which facilitate real-time monitoring of vessel positions. These systems contribute to preventing illegal fishing, protecting marine areas, better enforcement regulations, and more precise ecological impact assessments (Cheng, Zhang, Chen & Wang, 2023).

c. *Internet of Things (IoT)*

The Internet of Things (IoT) represents a transformative concept in which physical devices are interconnected in a network, enabling them to collect, share, and process data automatically. They collect information about their surroundings and exchange data over the Internet and other communications networks. IoT devices apply AI and machine learning (ML) to predict and analyze data effectively. This integration allows devices to make informed decisions and improve their function without direct human intervention (Dupont, Cousin & Dupont, 2018; Figure 4).

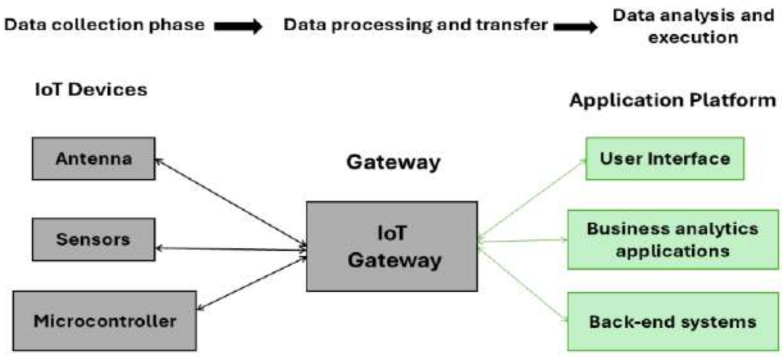

Figure 4. A typical composition of an IoT system (Mustapha et al., 2021; Sourceforge, 2020)

The automation and use of advanced IoT technologies like remote cameras, micro-and nanosensors, intelligent sorting, energy-saving processes, and bionic robot tools can revolutionize aquaculture by enhancing operational efficiency, monitoring fish health, and optimizing environmental conditions. With advanced optical sensor technology, the 'OxyForcis' manufactured and designed by 'Smalle Technologies, measures the temperature and oxygen levels in real-time, addressing critical parameters in both freshwater and marine systems in Spain. The system's ability to transmit data wirelessly to remote servers and display it on electronic units near ponds and cages simplifies decision-making for users. Providing data directly to smartphones or computers, empowers farm operators to respond quickly to environmental changes, enhancing productivity and minimizing risks (Martin, 2019). The integration of IoT in aquaculture demands advancements in information transmission technology to ensure efficiency, reliability, accuracy, connectivity, and secure communication. Li and Li (2020) identified six key requirements for effective IoT networking in aquaculture:

(1) Ensure seamless connectivity, unrestricted by geographical location or time, to facilitate real-time monitoring and decision-making.

(2) Achieve rapid data transfer rates, ranging from 1000 Mbps to 1 Gbps, to support vast amounts of data generated by IoT devices.

(3) Enable centimeter-level positioning accuracy and reduce network delay to microseconds, ensuring timely and accurate data transmission.

(4) Guarantee high reliability, minimal network interruptions, and support for high-density connection (up to 100 devices per cubic meter).

(5) Facilitate deep integration with various networks business systems and emerging technologies such as AI

(6) Implement strong security measures to resist network attacks, detect potential threats, and trace the sources of attacks, ensuring the integrity of aquaculture data.

d. *Cloud computing*

Cloud computing refers to the use of a network of remote servers hosted on the Internet for management, storage, and data processing, instead of relying on local servers or personal computers. Cloud computing is deployed in several ways: public, private, on-premises, or hybrid model, where a combination of on-premises infrastructure and cloud services is utilized (Figure 5). There are three primary service models in cloud computing:

Platform as a service (PaaS): designed for developers, provides a platform to develop, run, and manage applications without the complexities of managing the underlying hardware or software infrastructure.

Infrastructure as a Service (IaaS): designed for system administrators (AWS), this model provides virtualized computing sources such as virtual machines, storage, and networks enabling businesses to manage their infrastructure without physical hardware.

Software as a Service (SaaS): designed for customers, this model delivers software applications via the cloud, eliminating the need for installation and local management.

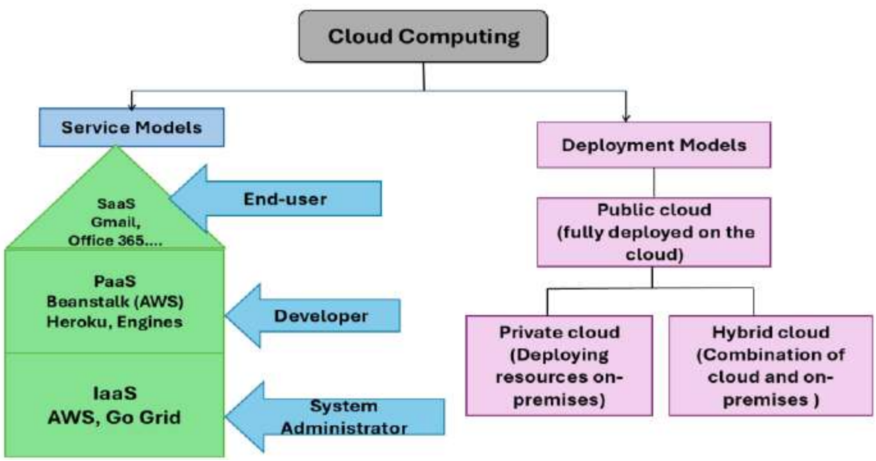

Figure 5. A detailed visualization of the various types of cloud computing services and deployment models (Mustapha et al., 2021)

Cloud computing plays a vital role in collecting and storing data generated from various stages like sales, production, and processing (Yongqiang, Shaofang, Hongmei, Pin & Yilin, 2019). With the help of cloud computing and advanced data technologies, aquaculture operations can gather large datasets that can be used to analyze enhance production efficiency, optimize farming methods, and improve decision-making. Cloud computing enables real-time monitoring of critical factors such as feed consumption, fish health, and growth rates. Additionally, they support traceability and method optimization that help compliance with protocols and regulatory guidelines, ensuring sustainable practices. The integration of CIA (Confidentiality, Integrity, and Availability) with a smart aquaculture system indeed plays a critical role in ensuring the system's reliability, flexibility, and performance. The use of cloud computing, as in the case of AquaCloud developed by the Seafood Innovation cluster in Norway in collaboration with IBM and several other companies, is an excellent example of how technologies can optimize aquaculture operations.

Cloud computing provides an excellent platform for the integration of various sub-systems such as data processing, water quality monitoring, fish health management, and data intelligent systems, into a single ecosystem. Such a method is designed on IBM clouds to monitor and predict sea lice outbreaks in aquaculture. By capturing sea lice counts and related data from various farms, the system helps farm managers assess risk levels and take preventive steps to prevent outbreaks. The predictive model helps to forecast trends over time, allowing for better-informed decisions. This kind of platform is crucial in minimizing the impact of sea lice infestations on fish health and farm productivity (Hoel, 2018).

e. *Machine Learning*

The rapid advancements in sensor technology, coupled with affordable data storage and increased computational have revolutionized data collection. The bottleneck in processing and analyzing vast datasheets highlights the urgent need for innovative and automated workflows (Malde, Handegard, Eikvil & Salberg, 2020; Rubbens et al., 2023). These workflows must integrate advanced techniques like machine learning (ML), AI, and big data analytics to efficiently handle, interpret, and extract meaningful insights from raw data. The upsurge of machine learning (ML) holds great promise for automatic complex and time-consuming steps in the analysis of ecological and fisheries management challenges. The initial step-up of ML systems and automated workflows demands significant investment in terms of time, expertise, and resources and the long-term benefits are substantial (Taconet, Kroodsma & Fernandes, 2019). These systems have the potential to alleviate resource constraints, enhance consistency in analyses, and effectively address the growing complexity of ecological processes ultimately supporting more informed and efficient management decisions (Fernandes-Salvador et al., 2022).

ML refers to the use of mathematical and statistical models that enable systems to learn and perform specific tasks without explicit programming and instructions. ML tasks can be broadly categorized into four main categories: supervised, unsupervised, semi-supervised, and reinforcement learning (Figure 6).

Unsupervised learning: this model works with unlabeled data and aims to uncover the hidden patterns and structures within the data. This is frequently used in factor dimensionality reduction (Farahat et al., 2013), customer grouping (Darena, Zizka, & Burda, 2012), and cluster analysis (Bakshi, Jagadev, Dehuri & Wang, 2014).

Supervised learning: this type involves training a model on a labeled datasheet, where input data is paired with the corresponding output. The model learns to map inputs to the correct outputs, making it useful for tasks such as classification and regression (Ghiassi & Lee, 2018).

Semi-supervised learning: Semi-supervised learning is a learning method combining supervised learning with unsupervised learning. This method can realize the combination of classification, regression, and clustering. For illustration, spam identification (Yu, Chen, Jiang, Fu & Qin, 2017; Zhang, Wu & Cao, 2018).

Reinforcement learning: the model learns by constant interaction between the system and the outside world in the form of rewards and penalties. The goal is to develop a strategy to maximize cumulative rewards over time, often used in robotics, gaming, and decision-making systems. This is the more complex method of machine learning which mainly deals with the reasoning required in processes like unmanned operations (Faust, Palunko, Cruz, Fierro & Tapia, 2017), autopilot (Cheng & Zhang, 2018; Zhu, Wang & Wang, 2018), and neuroscience (Mnih et al., 2015) etc.

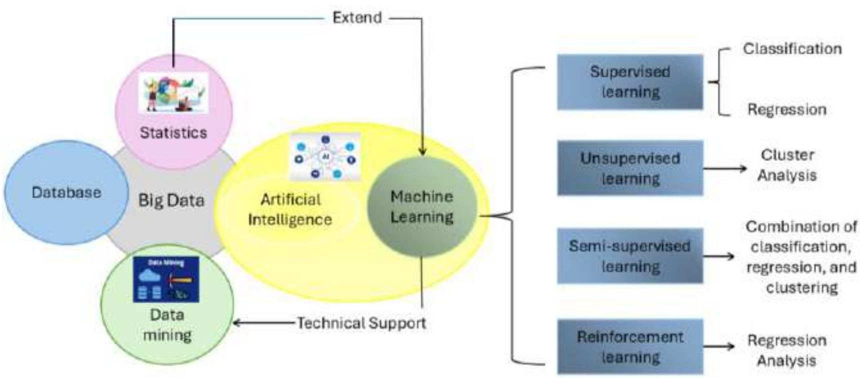

Figure 6. The relationship between four types of machine learning and common applications (Zhao et al., 2021)

f. *Deep learning*

Deep learning (DL), a subset of machine learning (ML), is utilized in artificial neural networks (ANN) that require understanding and extracting intricate patterns from vast and complex datasheets. Convolutional neural networks (CNN) have revolutionized fields like image and video analysis due to their ability to capture temporal and spatial dependencies by applying context-dependent filters across input data (Schneider, Taylor, Linquist & Kremer, 2019). DL-based feeding decision-making research has advanced significantly in recent years, particularly in aquaculture. Accurate recognition of fish behavior using deep learning can revolutionize feeding management in aquaculture by optimizing feed utilization, lowering feed costs, enhancing growth performance, and reducing environmental impact (Rauf et al., 2019; Figure 7).

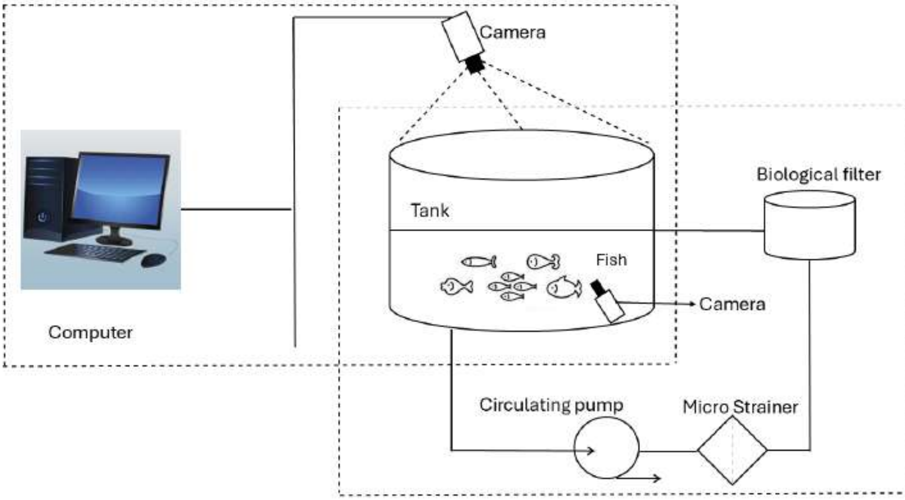

Figure 7. Diagnosis of computer vision-based fish behavior (Rauf et al., 2019; Yang et al., 2024)

Challenges

Aquaculture's contribution to global fish production has steadily increased over the years, reaching 46 percent in 2016-2018 compared to 40.1% in 2011, 42.6% in 2012, 43.7% in 2013, 44.7% in 2014, and 45.1% in 2015. This trend highlights the growing role of aquaculture in sustaining global fish supplies (FAO, 2018, 2020). However, this steady growth is not without challenges. Technological advancements are required to overcome these problems, such as disease outbreaks, water pollution, quality of broodstock and fingerlings, and poor management practices (Fearghal, 2019; Michael, 2019).

The exploitation of marine resources, if not managed sustainably, can lead to significant environmental consequences. Overfishing, habitat destruction, and pollution are some of the key issues that disrupt marine ecosystems, leading to loss of biodiversity, declining fish populations, and the collapse of the food chain. These impacts not only threaten marine life but also have negative effects on coastal communities, global food security, and climate regulation. The impact of fishing, particularly on species with low reproductive rates, can be far-reaching. In addition to the direct effects on target species, the broader implications include damage to marine biodiversity, shifts in the food chain, and the degradation of habitats. Marine fishing faces several challenges, some of the key ones include (Islam, Sadia, Masuduzzaman & Shin, 2020; Tolentino-Zondervan, Ngoc & Roskam, 2023).

Overfishing

Overfishing is indeed a major issue affecting the marine ecosystem. When the fish population is overexploited, they don't have enough time or numbers to regenerate, leading to the collapse of stocks, which can impact the fish and the broader marine food web. Bottom trawling is highly damaging to marine habitats, as it scrapes the ocean floor, destroying coral reefs and other delicate ecosystems. In addition to environmental destruction, overfishing often leads to the generation of plastic waste, as fishing gear and plastics become entangled in the ocean, harming marine life and contributing to the growing global plastic pollution crisis. Water pollution is caused by waste, chemicals, and hydrocarbons from various types of vessels such as fishing boats, transport ships, oil tankers, and tourist boats,which poses a serious threat to water quality and marine ecosystems (Chukkapalli et al., 2021).

Inadequate fisheries management

Ineffective and inadequate fish management practices can significantly impact aquatic ecosystems and the fishing industry. Lux regulations and oversight can result in overfishing, population imbalances, conflicts among fishermen, overexploitation, habitat destruction, and fishing in polluted areas or the use of harmful practices that reduce the overall health and quality of fish.

Impacts of climate change

Climate change and fishing practices play significant roles in disrupting marine biodiversity. It affects the oceans by rising sea temperatures, changes in sea currents, ocean acidification, and the distribution of aquatic species which disrupts the food chain and fisheries habitats (Xu, Shi, Sun & Shen, 2019).

Loss of Biodiversity

Fishing can lead to by-catches in which endangered species and non-targeted species are often caught, leading to population decline. Overfishing can deplete the fish stocks and disrupt ecological balance. The use of destructive fishing gear, like trawling can destroy the seabed habitats, further reducing the marine biodiversity (Probst, 2020).

Socio-economic issues

Fishing communities depend on marine resources for their livelihoods. Fishing communities face significant challenges related to competition, economic stability, and the equitable distribution of fishing benefits (Zhang, Wang, Aujla, Jindal & Al-Otaibi, 2023).

Labeling and Traceability

Accurate identification and traceability of fish products through the food chain are critical issues against illegal, unreported, and unregulated fishing (Leal, Pimentel, Ricardo, Rosa & Calado, 2015). The rising demand for traceability in the fisheries and aquaculture industries has forced organizations to expand their services and programs to ensure transparency, sustainability, and accountability in supply chains. Companies have unique traceability requirements that depend on location, size, supply chain position, and product types. However, companies at the end of the supply chain, such as retailers and those directly dealing with consumers, face unique challenges due to diverse product ranges, to handle and analyze large amounts of data and consumer demand transparency regarding sourcing, sustainability, and ethical practices, adding pressure on retailers (Lewis & Boyle, 2017). Implementing durable, user-friendly traceability tools is essential for ensuring accurate data collection to address the challenges harvesters face near the point of harvest. Effective monitoring and sharing of input and output data in aquaculture are essential for sharing information about traceability, transparency, and sustainability throughout the supply chain.

Applications

Technological advancement in aquaculture plays a significant role in addressing the challenges posed by increasing population growth and high demands for fish products. These techniques control fish prices, protect wildlife stocks, and increase productivity. The rising global population and the increased demand for seafood can put tremendous pressure on wild fish stocks leading to overfishing, and depletion of these valuable resources. Research and Development (RD) in aquaculture technology could play a crucial role in addressing these challenges by improving the sustainability of fish production, alleviating poverty, improving social welfare, and preserving marine biodiversity.

Blockchain technology is a powerful tool that significantly improves the aquaculture industry in several key areas as blockchain ensures all transactions are in sequence, whether they capture fish or their distribution across the supply chain, are recorded. A transaction contains a smart contract invocation and a value transfer. It is a distributed and immutable digital ledger that records transactions and tracks assets in a business network using cryptographic algorithms. Transparency is essential for tracking seafood from source to consumer to ensure that products are sustainably sourced. With the help of blockchain, every catch and product can be traced from the source to the consumer. It aids in meeting sustainable standards and in managing certifications for sustainable practices.

Artificial intelligence (AI) can analyze datasets to forecast fish populations, detect illegal fishing activities, and optimize fishing practices. It is less labor intensive and correlates the fish behavior changes with water quality parameters like dissolved oxygen (DO), temperature, and pH. It is widely used in classification, feed optimization, stress, and disease detection, and helps to prevent overfishing and maintain biodiversity in aquatic environments. With the help of AI, aqua culturists can make data-driven decisions that balance the need for economic development with the protection of marine resources. AI algorithms can analyze environmental data and suggest optimal catch limits, fishing zones, and help to design more effective conservation strategies.

The Internet of Things (IoT) is a transformative technology that connects devices and systems to collect, exchange, and process data leading to smarter environments. It enables network sensors and devices to remotely connect, monitor, track, and manage products and systems in real-time. It facilitates communication between physical and digital environments. It enhances efficiency, automation, and decision-making by enabling real-time data monitoring and control. It enables devices to communicate and operate without human intervention, reducing manual workload. It automates routine tasks, increasing productivity and minimizing errors. IoT continues to evolve, and its integration into daily life will expand but it will also require security frameworks, data management strategies, and infrastructure development.

The machine learning (ML) powered monitoring system automatically detects anomalies in water quality, fish behavior, and other parameters, enabling the aqua culturist to respond quickly to potential issues. It helps to analyze the data from genetics and breeding programs to identify superior traits and improve the overall quality of broodstock. It enables the systems to learn and improve from data without explicit programming. It has transformed industries by enabling predictive analytics, automation, and intelligent decision-making in different areas. With ongoing advancements in algorithms, computational power, and data availability, the future of ML promises even greater contributions to solving complex real-world problems.

Deep learning (DL) algorithms can enable autonomous systems like drones, and robots to sort fish based on size, weight, or quality using image recognition. It can handle complex data like images, videos, and audio files, and extract relevant features. It helps to optimize the real-time processing and make them suitable for large datasets that require fast and accurate results. It detects stress patterns and abnormal swimming behavior, which helps prevent diseases and improve overall fish health. It analyzes environmental data to predict harmful algal blooms and pathogen outbreaks. It prevents water contamination and fish mortality. It supports precision aquaculture, reducing waste and increasing farm efficiency.

Cloud computing reduce feed waste by adjusting feed behavior based on fish behavior, improving the feed conversion ratio. Sensors detect feeding activity, stress levels, and movement patterns, and identify early signs of disease for better management. Real-time monitoring of dissolved oxygen, temperature, and pH ensures a healthy environment. It helps to track and reduce unintentional catches of non-target species. It supports marine ecosystem-based fisheries management by analyzing data on fish populations, habitats, and ecosystem interactions. It can facilitate stakeholder engagement and participation in fisheries management decision-making processes.

Conclusion

The aquaculture industry has significantly increased by integrating digital technologies including IoT, AI, blockchain, ML, DL, and big data analytics. These tools enhance decision-making, improve efficiency, water quality monitoring, fish tracking, and individuality, and maintain optimal conditions for fish welfare by enabling real-time monitoring, predictive analytics, and automation. By addressing the power of these technologies and critical challenges in aquaculture including operational inefficiencies, environmental sustainability, disease management, and resource optimization we can work towards a future where our oceans are managed more effectively and responsibly for the benefit of present and future generations. In brief, our purpose in writing this review was to provide researchers and practitioners with a better understanding of the current applications of digital technologies in fish farming and to facilitate the application of digital technologies to solve practical problems in aquaculture.

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CHAPTER II

A HOLISTIC APPROACH INTEGRATING EXPLORATORY DATA ANALYSIS AND MACHINE LEARNING FOR CHARACTERIZING AQUACULTURE FACILITIES IN TÜRKİYE

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INTRODUCTION

The increasing global population, urbanization, climate change, and the risk of depletion of natural resources have driven humanity toward new approaches for sustainable and secure food production (Béné et al., 2015; Teng, 2024). In this context, aquaculture has emerged not only as a sector that continuously contributes to national economies worldwide, but also as a strategic production area in terms of environmental sustainability, food security, and rural development. In Türkiye as well, interest in this field has grown significantly in recent years, accompanied by rapid sectoral growth supported by government incentives, regulatory frameworks, and private sector investments (TUIK, 2024). As a result of the efficient utilization of marine and inland water resources, aquaculture has developed as an alternative method to traditional fishing and now constitutes a significant portion of total fisheries production. This shift has not only reduced the fishing pressure on natural stocks but also contributed to the establishment of a climate-resilient food production system. In addition to being a key tool in ensuring food supply security, aquaculture supports economic and social development in coastal and rural areas by providing employment opportunities (FAO, 2022; TUIK, 2024). Moreover, recent technological advances in areas such as biotechnology, digital monitoring systems, and sustainable feed technologies have increased production efficiency and offered solutions aimed at minimizing environmental impacts. In light of all these developments, aquaculture has become a strategically important production model that must be supported by integrated policies both nationally and globally (Mustafa et al., 2021; Duguma and Bai, 2024; Areti et al., 2024).

Aquatic products play a vital role in human nutrition due to their high biological value in protein content, abundance of omega-3 fatty acids, and richness in vitamins and minerals (Sharma et al., 2024; Singh, 2024). However, increasing water pollution, excessive and unregulated fishing, global climate change, and the decline of fish stocks are creating both environmental and anthropogenic pressures that threaten biodiversity in marine and freshwater ecosystems, thereby jeopardizing the sustainability of these resources (Yesilsu et al., 2024). In this context, aquaculture has emerged as a strategic alternative to ensure food supply security and reduce the pressure on natural stocks. Thanks to controlled production conditions, aquaculture stands out as a relatively low-impact, traceable, sustainable, and highly efficient model of food production (Pradeepkiran, 2019; Bjørndal et al., 2024). This system, which plays an increasingly important role in meeting the global demand for fish protein, not only contributes to the conservation of natural stocks but also alleviates pressure on terrestrial agricultural land, promotes sustainability in land use, and significantly reduces environmental footprint compared to traditional livestock farming due to lower water and feed requirements. Moreover, the integration of advanced technologies into the aquaculture sector has resulted in more efficient production processes, more effective disease management, and greater transparency in traceability. These advancements have positioned aquaculture not merely as a method of food production, but as a strategic tool for environmental and economic sustainability in the development of the blue economy (Yue and Shen, 2022; Ruby et al., 2022; Rowan, 2023).

Aquaculture reached a production volume of 130.9 million tons in 2022, supplying approximately 15% of the global animal protein demand and thereby making a significant contribution to food security (FAO, 2022). In the same year, the sector provided direct and indirect employment to more than 20 million people and generated a farm-gate value of 312.8 billion USD. These figures demonstrate that aquaculture plays a critical role not only in food production but also in socioeconomic development. With a total output of 94.4 million tons (excluding algae), aquaculture accounted for 51% of the world's total aquatic production, surpassing capture-based fisheries. Notably, aquatic animal products intended for human consumption reached a historic record with a 57% share (Verdegem et al., 2023). This trend reflects a growing consumer preference for seafood sourced from safe, sustainable, and traceable origins, and highlights the sector's success in meeting this demand. In terms of production details, inland aquaculture led with 59.1 million tons, while marine and coastal aquaculture contributed 35.3 million tons. This diversity points to a flexible production structure capable of adapting to a variety of ecological conditions (FAO, 2022). Aquaculture presents a vital solution for feeding the growing global population sustainably. At the same time, it helps protect marine ecosystems by mitigating the environmental damage caused by overfishing and promotes both environmental and social sustainability in alignment with the Sustainable Development Goals (SDGs). Thanks to innovative approaches such as emerging technologies, genetic improvement programs, sustainable feed alternatives, and integrated production systems, the aquaculture sector continues to secure a strategic position within the food systems of the future (Troell et al., 2023).

Türkiye possesses a natural advantage in aquaculture due to its geographical position surrounded by seas on three sides, abundant inland water resources consisting of lakes and rivers, and favorable climatic conditions (Kayıs, 2019) (Figure 1). These geographical and ecological advantages place Türkiye among the leading countries in terms of aquaculture production potential. In recent years, the sector has gained significant momentum as a result of the widespread adoption of modern farming techniques, the expansion of R&D activities, and the effective implementation of government incentives. The share of aquaculture in Türkiye's total aquatic production has been steadily increasing, and the country now ranks among Europe's top producers of high-value species such as gilthead sea bream (*Sparus aurata*), European sea bass (*Dicentrarchus labrax*), and rainbow trout (*Oncorhynchus mykiss*) (Hough, 2022). According to 2024 data, rainbow trout is the most cultivated species in inland waters with a production of 152,566 tons, while among marine species, sea bass and sea bream rank first with 160,802 tons and 154,011 tons, respectively (DGFA, 2024). Furthermore, within the scope of marine aquaculture, as of 2023, Türkiye produced 8,738 tons of mussels, 6,149 tons of juvenile mussels, and 3,674 tons of tuna (TURKSTAT, 2023).

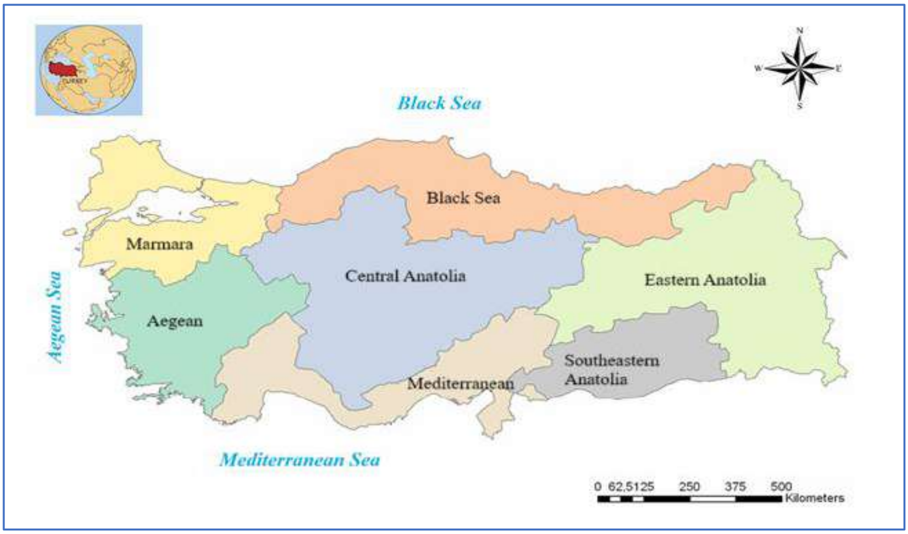

Figure 1. Regional map of Türkiye. Modified from (https://www.mappr.co/counties/turkey-regions/) and (https://www.nationsonline.org/oneworld/map/turkey-map.htm)

In Türkiye, aquaculture is primarily based on sea cage systems installed in marine areas and concrete pond systems used in inland waters (Figure 1). Although these systems offer high production efficiency, the pressures they place on the environmental carrying capacity of coastal areas and their impacts on ecosystem health are among the major factors that threaten long-term sustainability. In this context, the pursuit of a more sustainable production model in aquaculture has brought recirculating aquaculture systems (RAS) to the forefront. RAS are closed-loop production systems in which water is continuously filtered and reused, minimizing interaction with the external environment and reducing the risk of disease transmission. These systems offer significant advantages, especially during the hatchery phase, in terms of high operational control and environmental sustainability. They are also supported by the Turkish government through various subsidy and incentive programs. However, the adoption level of RAS in Türkiye is still limited. The main reasons include high initial investment costs, energy intensity, the need for technical expertise, and operational complexity (Arifa et al., 2022; Song et al., 2019; Zhang et al., 2023; Fong et al., 2024). Nevertheless, considering factors such as climate change, resource scarcity, and increasingly strict environmental regulations, the widespread adoption of RAS in Türkiye appears inevitable in the long term. In this regard, in addition to government support, the expansion of these systems through university-industry collaborations, technical training programs, and domestic technology development initiatives is of strategic importance.

In parallel with these developments, the aquaculture sector has become one of Türkiye's few agricultural sub-sectors generating a foreign trade surplus and has begun to make significant contributions to the national economy by consistently increasing its export volume, particularly to European countries. As of 2023, aquaculture production in Türkiye reached 1,010,346 tons, representing an 8% increase compared to the previous year. In the same year, capture-based production amounted to 454,059 tons, while aquaculture-based production reached 556,287 tons. These figures clearly demonstrate that aquaculture has now surpassed capture fisheries in overall aquatic production. Approximately 55% of Türkiye's total aquaculture production is derived from farming activities, of which 72% occurs in marine environments and 28% in inland waters. In 2023, 399,529 tons were produced from marine aquaculture, whereas 156,758 tons were produced from inland waters. When trends over the past decade are examined, marine production has consistently outpaced inland production, indicating Türkiye's growing capacity in cultivating marine species such as sea bream, sea bass, and tuna.

The aquaculture sector also stands out in terms of export performance. By 2023, export revenues from the sector had reached 1.7 billion USD. Türkiye exports aquaculture products to more than 100 countries, primarily to

European Union member states. This broad export network reflects the sector's success in meeting growing global demand and its increasing international competitiveness. Today, aquaculture is not only an economically significant activity but also holds strategic importance for food security, sustainable production, and rural development. In line with Türkiye's 2030 goals, the sector has the potential to further strengthen its role as a key export commodity and continue contributing to the country's trade surplus (Aydın et al., 2025). Beyond its economic contributions, aquaculture plays a strategic role in supporting rural development and increasing employment opportunities. Through its sub-sectors such as hatchery operations, farming, processing, logistics, and marketing, the industry provides direct or indirect employment to thousands of individuals and contributes to retaining the rural population in their local communities, thereby helping to reduce internal migration (Korkmaz and Doğu, 2020).

The number of employees in the aquaculture sector in Türkiye increased steadily from 5,100 in 2003 to 8,500 in 2012, and reached 11,200 by 2022 (TUIK, 2024). This growth in employment is directly related to both the expansion of production capacity and the widespread adoption of modern aquaculture technologies. For example, in the province of Muğla alone, a total of 2,127 people are employed across 327 fish farms, of which 24.8% are aquaculture engineers and technicians, while the remaining 75.2% consist of other support personnel. This clearly indicates the sector's growing need for technical expertise (TUIK, 2024).

Another significant component of aquaculture in terms of employment is fish feed production. According to a survey conducted by Yıldırım (2012), a total of 355 people were employed in 18 fish feed factories operating across Türkiye. Among these employees, 33 were aquaculture engineers, 15 were agricultural engineers, 8 were chemists, 6 were veterinarians, 5 were technicians, and the rest were classified as general laborers. Today, the number of fish feed factories has increased to 29 across 15 provinces, and correspondingly, both production capacity and employment volume have grown substantially (Yıldırım, 2023). This development highlights the sector's increasing capacity for vertical integration and underscores the strategic importance of utilizing more domestic resources in feed production.

However, there are several major challenges that threaten the sustainable growth of the aquaculture sector. These include the impacts of climate change, dependence on imported feed components, pollution of water resources, nearing the ecological carrying capacity of production areas, and the increasing risk of disease outbreaks. Addressing these issues requires a holistic approach that incorporates not only technical but also socioeconomic and environmental dimensions.

In this context, encouraging innovation, implementing policy reforms to reduce environmental impacts, and integrating advanced technologies into production processes are all of great importance for the sustainability of the sector. The current status and future trends of fish farming in Türkiye must be re-evaluated by researchers, policymakers, and industry stakeholders. Establishing data-driven decision-making processes and developing strategic planning are essential steps to ensure stable and balanced growth in the sector. The aim of this study is to provide a detailed analysis of the structural dynamics of the aquaculture sector in Türkiye by examining the regional distribution of aquaculture facilities, the species being cultivated, their project capacities (kg), fry and egg production capacities, and the production methods employed. The findings will serve as a guide for strategic planning to make more effective use of the country's aquaculture potential.

MATERIALS AND METHODS

The dataset used in this study is based on the publicly available information published on the official website of the Ministry of Agriculture and Forestry of the Republic of Türkiye regarding "aquaculture facilities" as of December 16, 2024 (TOB, 2025). The study consists of two main stages. In the first stage, the aquaculture facilities in Türkiye were characterized using an Exploratory Data Analysis (EDA) approach based on descriptive statistical methods. The analysis focused on the following variables by region: species cultivated, project capacity (kg), fry capacity (units), egg capacity (units), and production methods. In the second stage, Principal Component Analysis (PCA) integrated with the Random Forest machine learning method was applied to determine which variables contributed most significantly to the differences observed between regions in terms of the aforementioned factors. Facilities cultivating more than four species were categorized as "multi," while the others were classified using specific abbreviations, as shown in Table 1.

Tablo 1. Species and their acronyms sased on cultivated aquatic species

Species	**Acronym**		**Species**	**Acronym**
Multiple species (more than 4 species)	Multi		European seabass (*Dicentrarchus labrax*)	L
Abant trout *(Salmo abanticus)*	Aa		Blue crab (Callinectes sapidus)	Myen
Mediterranean mussel (*Mytilus galloprovincialis*)	Amkm		Common pandora (*Pagellus erythrinus*)	Mef
Aquarium fish	Akv		Bester sturgeon (Hybrid of *Huso huso* × *Acipenser ruthenus*)	Mhb
Mediterranean trout (*Salmo cettii*)	Abbda		Ship sturgeon (*Acipenser nudiventris*)	Mk
Caspian trout (*Salmo trutta caspius*)	Ader		Beluga sturgeon (*Huso huso*)	Mm
Black Sea trout (*Salmo trutta labrax*)	Ak		Stellate sturgeon (*Acipenser stellatus*)	Msi
Brook trout (*Salvelinus fontinalis*)	Akay		Siberian sturgeon (*Acipenser baerii*)	Ms
White-legged shrimp (*Litopenaeus vannamei*)	Bbk		Meagre (*Argyrosomus regius*)	MiKo
Gilthead seabream (*Sparus aurata*)	Ç		Atlantic bluefin tuna (*Thunnus thynnus*)	Omy
Rainbow trout (*Oncorhynchus mykiss*)	Ag		White grouper (*Epinephelus aeneus*)	Sagr
Dwarf catfish *(Ictalurus melas)*	Kbd		Common carp (*Cyprinus carpio*)	Saz
Land snail (Helix *lucorum)*	Ksal		Spirulina (*Arthrospira platensis*)	Spr
Crayfish	Ker		Ornamental plant / Aquatic ornamental plant	Leech
Wedge clam (*Donax trunculus*) or Tellina (Tellinidae)	Kşt		Ornamental shrimp / Decorative shrimp	Sub
Sandworm (*Arenicola marina*)	Kumk		Ornamental Shrimp	Suk
Frog (*Pelophylax ridibundus)*	Kur		Catfish (*Silurus glanis*)	Ya

Data analysis was conducted using Microsoft Excel and appropriate packages available within the R ecosystem, including "randomForest", "ggplot2", "factoextra", "dplyr", and "cowplot".

RESULTS

The number of aquaculture facilities, project capacity, fry capacity, and egg capacity by region are presented in Table 2, Table 3, Table 4, Table 5, Figure 2, Figure 3, and Figure 4.

Number of Facilities by Region for Cultivated Species

The Aegean Region hosts more than one-quarter of the total aquaculture facilities in Türkiye (26.15%), making it the region with the highest facility density nationwide. This can be attributed to its long coastline, well-established marine production infrastructure, favorable climatic conditions, and strong private sector investments. The region particularly stands out in the cultivation of gilthead sea bream, sea bass, and multi-species production. The Black Sea Region ranks second (21.13%), distinguished by its high concentration of facilities specialized in rainbow trout farming. This density is primarily due to the abundance of freshwater resources and water temperatures suitable for trout production. Despite its high altitude and cold climate, the Eastern Anatolia Region (19.17%) exhibits significant development in rainbow trout (*Oncorhynchus mykiss*) cultivation. This is mainly due to the availability of clean, cold-water resources and the influence of government-supported investments. The Mediterranean Region (16.21%) is prominent in marine species production, particularly gilthead sea bream and sea bass. The region has strong potential thanks to the applicability of cage systems and offshore aquaculture technologies. The Central Anatolia Region, with a relatively low facility share (7.65%), includes a notable proportion of hatcheries and egg production units. This indicates that the region is more specialized in fry and egg production rather than grow-out operations. In the Marmara Region, which has a high density of industrial activity, aquaculture production is relatively limited (5.74%). However, there are some localized production hubs attracting attention, particularly for species such as "Amkm". The region with the lowest facility density is Southeastern Anatolia (3.97%). Climatic and hydrological conditions in the region restrict aquaculture activities, and production is mostly limited to trout-oriented facilities.

The geographical distribution of aquaculture facilities in Türkiye varies depending on factors such as climatic conditions, the quality and quantity of water resources, technological infrastructure, and market accessibility. While the Aegean and Black Sea regions have high potential for both coastal and inland aquaculture, inland regions such as Eastern Anatolia have also emerged as significant production zones, particularly for cold-water aquaculture.

Number of Facilities by Cultivated Species According to Production Method

In the Mediterranean Region, the most common aquaculture system is the Concrete Pool system, used in 204 facilities. This is followed by Cage systems with 141 facilities. A significant portion of production in the region is concentrated around these two systems. Other systems are used to a much lesser extent, such as Soil Pools (21) and Tanks (4), which serve as supporting infrastructure. In the Eastern Anatolia Region, Cage systems dominate by a large margin, with 299 facilities. The second most used system is Concrete Pools with 106 facilities. These two systems account for nearly all of the production in the region. No use of other systems such as lake-based, soil pool, or tank systems has been observed. This indicates a highly homogeneous production structure in the region. The Aegean Region stands out for its diversity in aquaculture systems. Cage (212) and Concrete Pool (202) systems are the most widely used, while a significant number of Raft/Rope systems (128) suggest the cultivation of shellfish species such as mussels. Additionally, more modern or integrated systems such as RAS (11) and Tanks (15) are used relatively more frequently. This variety reflects the region's advanced technological infrastructure in aquaculture. In the Southeastern Anatolia Region, the most commonly used system is the Cage system (66 facilities), followed by Concrete Pools (14 facilities). The remaining systems are represented by only a few facilities. The region's generally low production capacity can be attributed to infrastructure limitations and geographical constraints. In the Marmara Region, the overall density of aquaculture facilities is relatively low. However, there are some notable features in terms of system diversity. The most widely used system is the Concrete Pool (52 facilities), supplemented by Raft/Rope systems (30 facilities). This suggests the presence of shellfish cultivation, such as mussels, in the region. In the Central Anatolia Region, the most commonly used systems are Concrete

Pools (81 facilities) and Cages (62 facilities). In addition, Lakes (6), Soil Pools (11), and Tanks (1) are also utilized. The variety of systems used in Central Anatolia aligns with the multi-purpose utilization of freshwater resources in the region (Figure 2-3, Table 2).

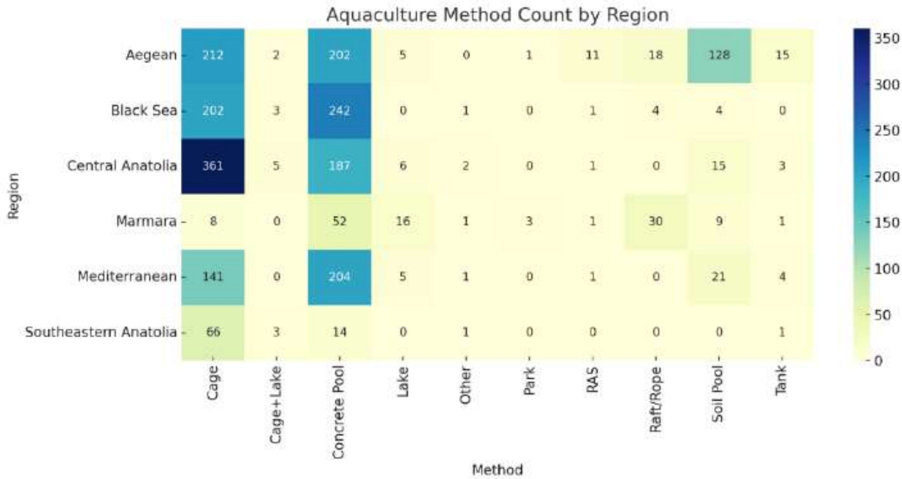

Figure 2. Regional distribution of aquaculture facilities in Türkiye in terms of production method

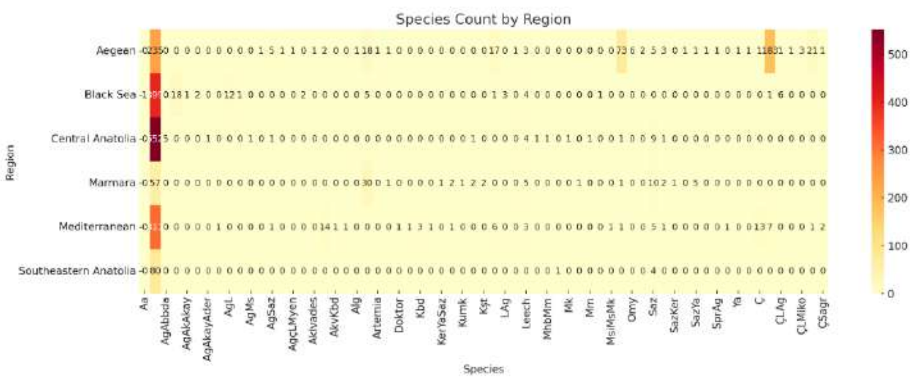

Figure 3. Regional distribution of aquaculture facilities in Türkiye in terms of species cultured

Table 2. Number of facilities by region for cultivated species

Species	Mediterranean	Eastern Anatolia	Aegean	Southeastern Anatolia	Central Anatolia	Black Sea	Marmara	Total
Ag	290	391	224	78	144	385	57	**1569**
AgAbbda		4						**4**
AgAk						18		**18**
AgAkAkay						1		**1**
AgAkayAder		1						**1**
AgAkL						2		**2**
AgAkvSaz	1							**1**
AgÇLAkv			1					**1**
AgçLMyen			1					**1**
AgL						12		**12**
AgLAk						1		**1**
AgMs					1			**1**
AgSav			1					**1**
AgSaz	1		5		1			**7**
Ak						2		**2**
Akivades			1					**1**
Akv								
AkvKbd	1							**1**
AkvSüsb								
Alg			1					**1**
Amkm			18			5	30	**53**
Artemia			1					**1**
Bbk			1				1	**2**
Ç	13		1					**14**
ÇL	7		170			1		**178**
ÇLAg			1			6		**7**
ÇLMef			1					**1**
ÇLMikö			3					**3**
ÇLSagr	1		21					**22**
ÇSagr	2		1					**3**
Doktor								
DoktorAkv	1							**1**
Kbd	3							**3**
KbdAkv	1							**1**
KerYaSaz							1	**1**
Ksal	1						2	**3**
Kşt							2	**2**
Kumk							1	**1**
Kur					1		2	**3**
L	6		17			1		**24**
LAg						3		**3**
LSagr			1					**1**
Mhb		1						**1**
MhbMm		1						**1**
MhbMmMk				1				**1**
Mk		1						**1**
MkAgAk							1	**1**
Mm		1						**1**
MsiAg						1		**1**
MsiMsMk	1							**1**
Multi	1		54					**55**
Omy			6					**6**
Sagr			2					**2**
Saz	5		5	4	9		10	**33**
SazAg	1	1	3				2	**7**
SazKer							1	**1**
SazTilap			1					**1**
SazYa							5	**5**
Spar			1					**1**
SprAg			1					**1**
SübSük								
Leech	3		3		4	4	5	**19**
Ya			1					**1**
Total	**339**	**401**	**547**	**83**	**160**	**442**	**120**	**2092**

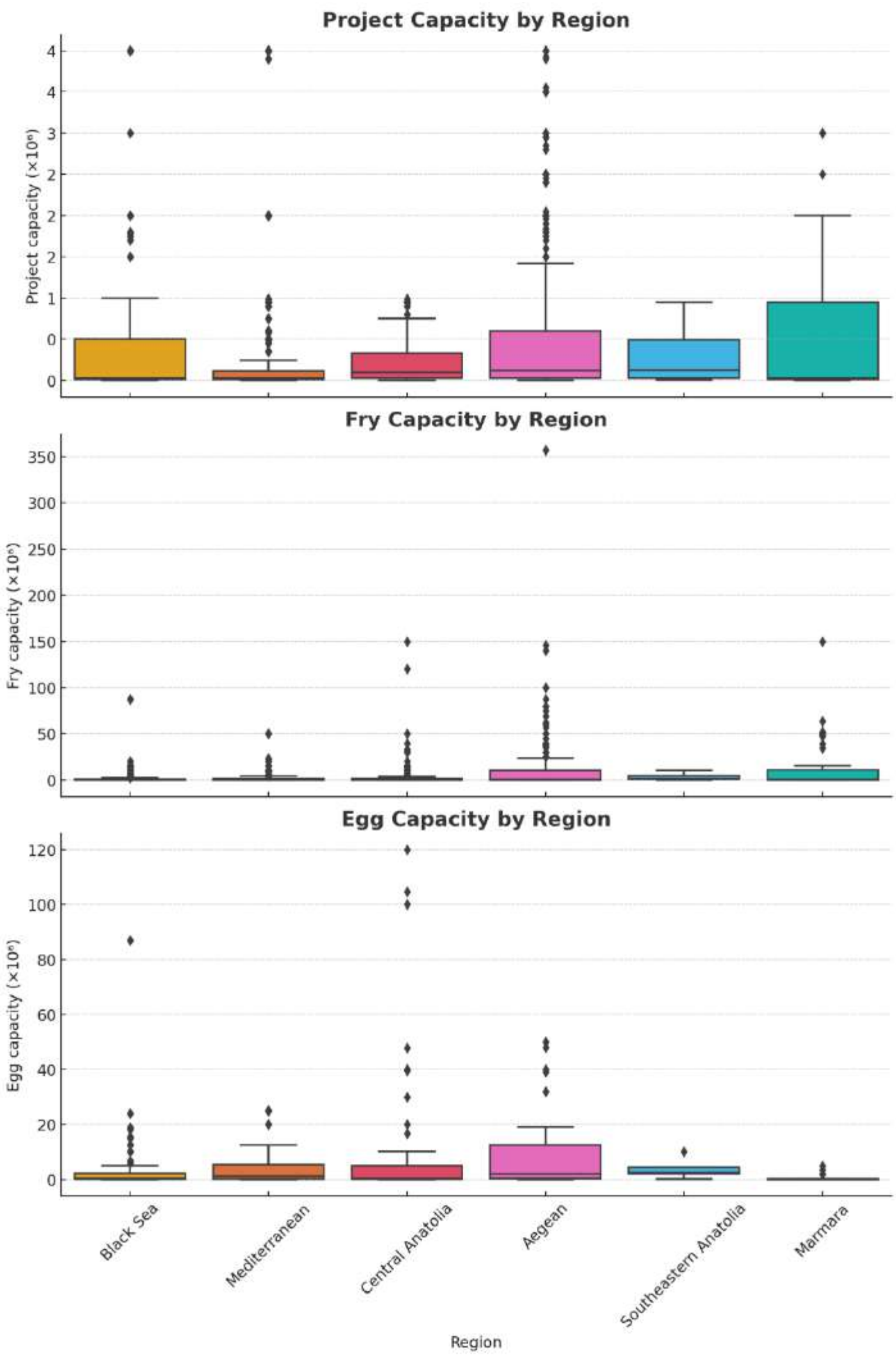

Figure 4. Regional Variation in Aquaculture Project, Fry, and Egg Capacities in Türkiye

Project Capacity (kg):

In terms of Project Capacity (kg), the highest total capacity belongs to the Aegean Region (281897550 kg), which shows that the region is the leader in production. The highest average project capacity is again seen in the Aegean Region (515515.6 kg/project), while the lowest average is in the Central Anatolia Region (265032.8 kg). The coefficient of variation (Cv) is the highest in the Mediterranean (2.6), which indicates a large heterogeneity among the projects. The lowest Cv is in Eastern Anatolia (1.2), where it can be said that the projects are more homogeneous. While the Aegean Region stands out with its high production capacity and high average per project, a wider range of capacities is observed in the Mediterranean. This may indicate the existence of some very large-scale projects (Table 3).

In terms of total project capacity (number), the cultivated species constitute 46.56% Ag, 22.29% CL, 7.99% Amkm, 4.86% Ç, 4.60% Multi, 3.64% L and 1.65% AgL. When the main species are considered, the total project capacity in the Mediterranean region according to the regions is: 35.93% Ç, 31.68% Ag, 16.91% CL, 8.01% ÇSagr, 4.07% L, 0.95% ÇLSagr, 0.60% Multi and 0.50% DoktorAkv; Eastern Anatolia: 96.37% Ag, 1.01% MhbMm and 0.86% AgAbbda; Aegean: 54.45% CL, 12.31% Multi, 10.55% Ag, 7.75% L, 5.20% ÇLSagr, 4.70% Amkm and 2.25% Omy; Southeastern Anatolia: 96.87% Ag and 2.76% MhbMmMk; Central Anatolia: 98.31% Ag, 1.17% AgSaz, 0.30% Reed, 0.15% AgMs, 0.07% Kur and 0.01% Leech; Black Sea: 77.33% Ag, 7.16% AgL, 3.20% AgAk, 2.80% AgAkL, 2.28% Amkm, 2.96% ÇLAg, 1.57% LAg and 1.13% L; Marmara: 86.62% Amkm, 11.60% Ag, 0.56% Kşt, 0.23% Kur, 0.26% Reed, 0.24% SazAg and 0.04% Bbk (Table 4).
Fry Capacity (Pieces):

The highest total fry capacity is in the Aegean Region (260146300 pieces), followed by the Mediterranean. Naturally, the highest average capacity is observed in the Aegean (1362022.4 pieces/project). The highest coefficient of variation (Cv = 4.1) is observed in Eastern Anatolia. This shows that there are large differences in the sizes of production facilities. The Central

Anatolia region also has a high average capacity (5846558.0), but this also comes with a fairly high standard deviation (17277879) and Cv (3.0). As a result, fry production is more widespread and homogeneously distributed in coastal regions such as the Aegean and Mediterranean, while in the inland regions it is both small in number and variable in size (Table 3).

In terms of total fry capacity (number), cultivated species constitute 37.00% Multi, 36.26% Ag, 15.27% Amkm, 7.86% ÇL. When the main species are considered, total fry capacity in the Mediterranean region according to the regions is: 95.61% Ag and 2.88% Akv; Eastern Anatolia: 88.10% Ag, 8.39% Multi and 3.05% AgAbbda; Aegean: 66.70% Multi, 15.44% Ag, 14.76% ÇL, 1.50% ÇLAg, 1.15% Amkm and 0.27% AgÇLMyen; Southeastern Anatolia: 100% Ag; Central Anatolia: 99.43% Ag, 40% Leech and 0.16% Kur; Black Sea: 76.41% Ag, 15.74% AgAk, 4.70% AgAkAkay, 1.97% MsiAg and 0.56% Leech; Marmara: 89.70% Amkm, 4.89% Multi and 3.26% Ag (Table 5).

Egg Capacity (Number)

The highest total egg capacity is in the Central Anatolia Region (493517005 units). Again, the highest average is noticeable in Central Anatolia (18278407.6 units/project). This may be due to the effect of several large egg production facilities. Eastern Anatolia and Marmara Regions have a heterogeneous structure in egg production with high Cv values (3.9 and 2.1 respectively). In Southeastern Anatolia, average production is high (3787500) but projects are few in number (4 projects). Central Anatolia seems to be specialized in egg production. The high average capacity and total capacity indicate the presence of a small number of large-scale production facilities in this region (Table 3). In terms of total egg capacity (number), the reared species are 83.94% Ag (rainbow trout), 7.15% Multi (more than 3 species), 3.16% AgAk (rainbow trout+Black Sea trout), 2.66% ÇL (Sea bream+Sea bass), 1.16% AgAkAkay, 0.17% Akv and 0.04% Aa. In the Mediterranean region, total egg capacity is 98.47% Ag, 1.21% Akv, 0.08% Kbd and 0.23% MsiMsMk species; Eastern Anatolia: 30.54% Ag, 3.17% Agbbda, 66.30% Multi; Aegean: 86.44% Ag, 13.46% ÇL, 0.07%

Leech and 0.03% Akv; Southeastern Anatolia: 100% Ag; Central Anatolia: 100% Ag; Black Sea: 75.21% Ag, 15.33% AgAk, 5.14% AgAkayAder, 3.32% MsiAg, 0.80% Leech, 0.20% Aa and 0.01% Ak; Marmara: 38.50% Ksal, 33.85% Ag, 26.95% Leech and 0.69% Frog (Table 6).

Table 3. Regional Distribution of Aquaculture Production Capacities in Türkiye

	Project Capacity (kg)					Fry capacity (number)					Egg capacity (number)				
Region	N	Total	Mean	Std	Cv	N	Total	Mean	Std	Cv	N	Total	Mean	Std	Cv
Mediterranean	339	99907820	294713.3	760041	2.6	162	334642609	2065695.1	5074209	2.5	55	193998826	3527251.4	5680150	1.6
Eastern Anatolia	401	94125500	234726.9	285661	1.2	109	393163197	3607001.8	14921732	4.1	34	157902751	4644198.6	17966067	3.9
Aegean	547	281987550	515516.5	830993	1.6	191	2601466300	13620242.4	34453573	2.5	27	289785080	10732780.7	16096905	1.5
Southeastern Anatolia	83	21719000	261674.7	285302	1.1	9	35905000	3989444.4	3814610	1.0	4	15150000	3787500.0	4287263	1.1
Black Sea	442	177002150	400457.4	766843	1.9	183	329465980	1800360.5	7067258	3.9	92	301649279	3278796.5	10000284	3.0
Marmara	120	50863935	423866.1	736241	1.7	60	798229271	13303821.2	26362527	2.0	19	12986000	683473.7	1407603	2.1
Central Anatolia	160	42405250	265032.8	348467	1.3	67	391719389	5846558.0	17277879	3.0	27	493517005	18278407.6	31274914	1.7

Overall, the Aegean and Mediterranean Regions stand out in terms of both the total number of projects and production capacity. The Central Anatolia Region demonstrates notably high values in egg production, indicating a regional focus on hatchery investments. Eastern Anatolia, while strong in project capacity, shows less development in fry and egg production. When considering the coefficient of variation (Cv, %), it becomes clear that there are substantial differences in facility sizes in certain regions. In Türkiye's aquaculture production, trout species (Ag and its subtypes) clearly dominate in project, fry, and egg production—particularly in inland regions. Marine species such as gilthead sea bream and European sea bass hold large shares in coastal regions, especially the Mediterranean and Aegean. Multi-species production (Multi) also plays an important role in both fry and egg output and is particularly widespread in the Aegean and Eastern Anatolia. Although limited, the production of alternative species (such as leeches and frogs) in some regions reflects the sector's growing diversification.

Table 4. Total project capacity (kg) for cultivated species by region

Species	Mediterranean	Eastern Anatolia	Aegean	Southeastern Anatolia	Central Anatolia	Black Sea	Marmara	Total
Ag	31652000	90710500	29749220	21040000	41687000	136868300	5901850	**357608870**
AgAbbda		805000						**805000**
AgAk						5666000		**5666000**
AgAkAkay						300000		**300000**
AgAkayAder		10000						**10000**
AgAkL						4950000		**4950000**
AgAkvSaz	10000							**10000**
AgÇLAkv			25000					**25000**
AgçLMyen			50000					**50000**
AgL						12672000		**12672000**
AgLAk						1700000		**1700000**
AgMs					65000			**65000**
AgSav			20000					**20000**
AgSaz	900000		1454000		495000			**2849000**
Ak						16000		**16000**
Akivades			300000					**300000**
Akv								
AkvKbd	29000							**29000**
AkvSüsb								
Alg			29000					**29000**
Amkm			13259000			4040000	44060000	**61359000**
Artemia			5000					**5000**
Bbk			29000				20000	**49000**
Ç	35900000		1420000					**37320000**
ÇL	16890000		153530500			750000		**171170500**
ÇLAg			10000			5236000		**5246000**
ÇLMef			2000000					**2000000**
ÇLMikö			208000					**208000**
ÇLSagr	950000		14650000					**15600000**
ÇSagr	8000000		600000					**8600000**
Doktor								
DoktorAkv	500000							**500000**
Kbd	170000							**170000**
KbdAkv	15000							**15000**
KerYaSaz							15000	**15000**
Ksal	20000						62000	**82000**
Kşt							300000	**300000**
Kumk							35000	**35000**
Kur					29000		114880	**143880**
L	4070000		21850000			2000000		**27920000**
LAg						2786000		**2786000**
LSagr			300000					**300000**
Mhb		250000						**250000**
MhbMm		950000						**950000**
MhbMmMk				600000				**600000**
Mk		600000						**600000**
MkAgAk							25000	**25000**
Mm		600000						**600000**
MsiAg						15000		**15000**
MsiMsMk	29000							**29000**
Multi	600000		34704000					**35304000**
Omy			6340000					**6340000**
Sagr			329000					**329000**
Saz	128000		93000	79000	127000		134000	**561000**
SazAg	44000	200000	314000				124000	**682000**
SazKer							22000	**22000**
SazTilap			200000					**200000**
SazYa							45000	**45000**
Spar			460000					**460000**
SprAg			29300					**29300**
SübSük								
Leech	820		530		2250	2850	5205	**11655**
Ya			29000					**29000**
Total	**99907820**	**94125500**	**281987550**	**21719000**	**42405250**	**177002150**	**50863935**	**768011205**

Table 5. Regional total egg production capacity (units) by cultivated species

Species	Mediterranean	Eastern Anatolia	Aegean	Southeastern Anatolia	Central Anatolia	Black Sea	Marmara	Total
Aa						600000		**600000**
Ag	191038826	48219004	250485080	15150000	493517005	226872879	4396000	**1229678794**
AgAbbda		5000000						**5000000**
AgAk						46244000		**46244000**
AgAkAkay						15500000		**15500000**
AgAkayAder								
AgAkL								
AgAkvSaz								
AgÇLAkv								
AgçLMyen								
AgL								
AgLAk								
AgMs								
AgSav								
AgSaz								
Ak						32400		**32400**
Akivades								
Akv	2350000		100000					**2450000**
AkvKbd								
AkvSüsb								
Alg								
Amkm								
Artemia								
Bbk								
Ç								
ÇL			39000000					**39000000**
ÇLAg								
ÇLMef								
ÇLMikö								
ÇLSagr								
ÇSagr								
Doktor								
DoktorAkv								
Kbd	160000							**160000**
KbdAkv								
KerYaSaz								
Ksal							5000000	**5000000**
Kşt								
Kumk								
Kur							90000	**90000**
L								
LAg								
LSagr								
Mhb								
MhbMm								
MhbMmMk								
Mk								
MkAgAk								
Mm								
MsiAg						10000000		**10000000**
MsiMsMk	450000							**450000**
Multi		104683747						**104683747**
Omy								
Sagr								
Saz								
SazAg								
SazKer								
SazTilap								
SazYa								
Spar								
SprAg								
SübSük								
Leech			200000			2400000	3500000	**6100000**
Ya								
Total	**193998826**	**157902751**	**289785080**	**15150000**	**493517005**	**301649279**	**12986000**	**1464988941**

Table 6. Total fry capacity (units) for cultivated species by region

Species	Mediterranean	Eastern Anatolia	Aegean	Southeastern Anatolia	Central Anatolia	Black Sea	Marmara	Total
Aa						500000		**500000**
Ag	319952609	346363197	401650300	35905000	389496389	251745980	26273271	**1771386746**
AgAbbda		12000000						**12000000**
AgAk						51846000		**51846000**
AgAkAkay						15500000		**15500000**
AgAkayAder		1800000						**1800000**
AgAkL								
AgAkvSaz								
AgÇLAkv			400000					**400000**
AgçLMyen			6900000					**6900000**
AgL								
AgLAk								
AgMs								
AgSav								
AgSaz								
Ak						1524000		**1524000**
Akivades								
Akv	9650000		400000					**10050000**
AkvKbd	100000							**100000**
AkvSüsb	1500000							**1500000**
Alg								
Amkm			30000000				716000000	**746000000**
Artemia								
Bbk								
Ç								
ÇL			384000000					**384000000**
ÇLAg			39000000					**39000000**
ÇLMef								
ÇLMikö								
ÇLSagr								
ÇSagr								
Doktor	300000							**300000**
DoktorAkv								
Kbd	320000							**320000**
KbdAkv	750000							**750000**
KerYaSaz								
Ksal							5050000	**5050000**
Kşt								
Kunk								
Kur					638000		4040000	**4678000**
L								
LAg								
LSagr								
Mhb								
MhbMm								
MhbMmMk								
Mk								
MkAgAk							4000000	**4000000**
Mm								
MsiAg						6500000		**6500000**
MsiMsMk	100000							**100000**
Multi		33000000	1735300000				39000000	**1807300000**
Omy								
Sagr								
Saz			2000000					**2000000**
SazAg							116000	**116000**
SazKer								
SazTilap								
SazYa			1500000					**1500000**
Spar								
SprAg			116000					**116000**
SübSük	450000							**450000**
Leech	1520000		200000		1585000	1850000	3750000	**8905000**
Ya								
Total	**334642609**	**393163197**	**2601466300**	**35905000**	**391719389**	**329465980**	**798229271**	**4884591746**

Variables Influencing Inter-Regional Differences

To better understand the regional differences among aquaculture facilities in Türkiye, a combination of machine learning and statistical analysis methods was applied. Within the scope of this study, a Random Forest model was used to determine the importance of facility characteristics (such as capacity and production methods) in classification. Subsequently, Principal Component Analysis (PCA) was performed to visualize regional similarities and differences in a two-dimensional plot (Figure 5).

The first of the resulting visualizations is titled "Random Forest Embeddings with PCA", which displays the distribution of facilities across regions based on PCA results with 65.91% accuracy. The second visualization, titled "Random Forest Variable Importance," illustrates the relative importance of the variables used in the analysis—such as egg capacity, fry capacity, project capacity, and production method—in classifying the regions (Figure 5).

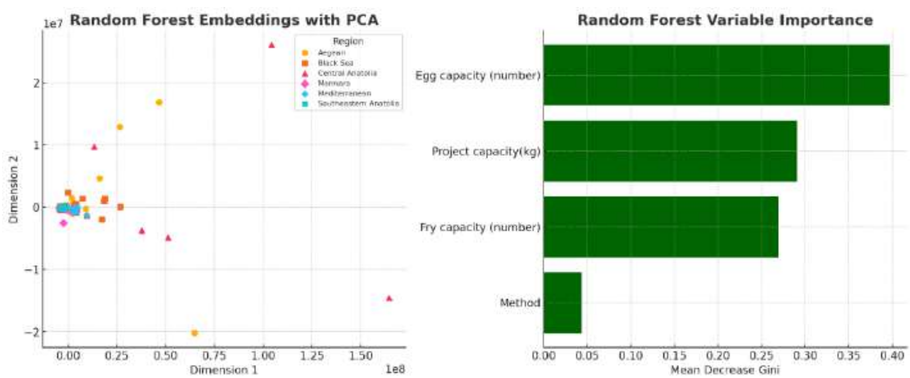

Figure 5. Random forest approach in regional classification: Analysis of PCA-based embedded representations and variable importance levels

Overall, it can be stated that the first principal component (Dimension 1) of the PCA analysis reflects the scale of total production capacity, while the second component (Dimension 2) captures differences in production type and focus. As a result, regions with similar capacity levels and production profiles tend to cluster together in the PCA space.

The Random Forest model revealed the extent to which specific variables contributed to the classification of aquaculture facilities by region. It was determined that egg capacity, fry capacity, project capacity, concrete pool farming, soil pool farming, and the park method were influential in distinguishing between regions. Among these, egg capacity (39.67%), project capacity (29.06%), and fry capacity (26.93%), and production and method (4.31%) together explained 96.97% of the total inter-regional variability. This indicates that the differentiation among regions is primarily driven by the scale of production and the structure of the production process.

Accordingly, the capacity-related variables not only contributed the most information to the model but also directly shaped the clustering patterns observed in the PCA visualization. On the other hand, structural variables such as production methods (e.g., concrete or soil pools, park method) had limited explanatory power in the Random Forest model and were largely ineffective in explaining regional separation. The main reason for this is that these methods are commonly used across many regions and show high correlation with capacity variables. In other words, information about the production method is often already inferred by the model through the capacity-related variables.

The two-dimensional distribution plot obtained from the PCA analysis (Random Forest Embeddings with PCA) visually reveals the similarities and differences among aquaculture facilities across Türkiye's geographic regions. In this plot, each point represents a low-dimensional embedding of a facility (or the regional average profile) from the corresponding region. Points that are close to each other indicate that the associated regions have similar characteristic profiles, whereas distant points suggest significant differences. Overall, the separation of regions in the PCA plot follows the patterns outlined below:

Aegean and Mediterranean Regions: These coastal regions are positioned close to each other in the PCA plane due to their high production capacities and similar aquaculture profiles. The Aegean Region, in particular, stands out for its large number of large-scale marine cage farms and hatcheries. While the Mediterranean Region also includes similar activities, it tends to operate on a somewhat smaller scale. However, in terms of overall production profile, it remains relatively close to the Aegean. This close proximity in the PCA plot can be attributed to the prevalence of marine fish farming and the generally large capacities of the projects in both regions.

Black Sea Region: The Black Sea Region is another prominent area with high total production capacity. While it is positioned relatively near the Aegean–Mediterranean group in terms of capacity, its differences in production methods and cultivated species cause it to deviate in a different direction on the PCA plot. As a result, although Black Sea facilities share similar capacity profiles with the Aegean, they form a distinct group along a separate component axis—likely due to differences in species and farming techniques.

Eastern and Southeastern Anatolia Regions: These two regions are grouped closely together in the PCA plane. Both are primarily engaged in inland aquaculture (e.g., trout farming in dam reservoirs and rivers) and host medium- to small-scale facilities. Although Eastern Anatolia includes some large-scale cage farms in dam reservoirs (e.g., Keban Dam), its overall capacity is not as high as that of the Aegean or Black Sea. Similarly, Southeastern Anatolia engages in reservoir cage aquaculture but remains one of the regions with the lowest total project capacities. Indeed, according to available data, the Aegean Region alone may account for approximately 50% of the total aquaculture capacity, while the share of Southeastern Anatolia is less than 5%. On the PCA graph, this is reflected in the distant positioning of Eastern and Southeastern Anatolia from the Aegean/Mediterranean group due to low capacity, while points from these two regions are close to each other.

Marmara and Central Anatolia Regions: Marmara and Central Anatolia appear either in intermediate positions or on the periphery of distinct groups in the PCA distribution. These regions do not fully belong to the high-capacity marine group nor to the low-capacity eastern group, and thus are positioned in the middle range on the graph. The Marmara Region exhibits a mixed production profile that includes both marine (e.g., mussel farming and limited marine cages) and inland systems (e.g., carp or trout ponds), though its total capacity is not very high. Central Anatolia, on the other hand, is predominantly engaged in inland fish farming (ponds and reservoirs) and ranks in the mid-range in terms of capacity. Therefore, on the PCA graph, points representing Marmara and Central Anatolia are located between the high-capacity coastal regions and the low-capacity eastern regions, maintaining some distance from both groups.

Conclusion

This study aimed to provide a multidimensional analysis of Türkiye's aquaculture sector by examining the structural and functional differences of aquaculture facilities at the regional level. Through an integrated approach combining exploratory data analysis and machine learning methods, a comprehensive characterization of the sector was achieved. Notably, egg capacity (39.67%), project capacity (29.06%), fry capacity (26.93%), and method (4.31%) were found to be the most influential variables, together explaining 96.97 % of the regional variation. These findings clearly demonstrate the significant diversity in production infrastructure and capacity scales across different regions. The regional classifications identified in this research offer valuable strategic insights for the future of the sector. The Aegean and Mediterranean regions have emerged as leading zones in Türkiye in terms of both production scale and facility diversity. These are followed by Central Anatolia, with its extensive hatchery infrastructure, while Eastern and Southeastern Anatolia are predominantly represented by smaller-scale, inland, and uniform production models. This distribution provides a clear roadmap for regional investment prioritization, infrastructure modernization, and capacity development planning. Moreover, the empirical strength of the methods used in this study extends beyond mere evaluation of current data, offering potential for model-based applications in decision support systems and strategic planning mechanisms. In this context, the development of decision support systems that emphasize capacity-oriented regional planning, environmental sustainability, technological integration, and economic efficiency is of great importance.

In conclusion, this research has clearly revealed the need for region-based strategic planning in the aquaculture sector and emphasized the importance of evidence-based management and decision-making. In the future, expanding the analytical framework to include variables such as environmental impacts, production costs, climate change adaptation, export potential, and social development will be a critical step in making Türkiye's aquaculture sector more resilient, competitive, and sustainable.

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CHAPTER III

REVIEW OF THE MONITORING METHODOLOGIES FOR SUSTAINABLE AQUACULTURE IN RESERVOIR FRESHWATER ECOSYSTEMS: FROM CHALLENGES TO PRACTICAL SOLUTIONS

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Introduction

Freshwater environments represent only a tiny fraction of the Earth's total water. These systems are vulnerable to human-induced stressors, including habitat destruction, land use changes, climate change, nutrient overload, and invasive species. The resulting ecological degradation and record-breaking rates of biodiversity change underscore the need for rigorous, repeatable monitoring of freshwater fish communities. Such programmes may aim to verify the presence of species, assess population trends of threatened taxa, and chronicle long-term shifts in entire assemblages. Regardless of their objectives, monitoring efforts can only be successful if the objectives are clearly defined and the data collected are tailored to achieve them.

In this review, we therefore emphasise the importance of explicitly stating monitoring objectives and review the range of sampling techniques available for freshwater fish. We highlight critical considerations, including sampling design, statistical power, detectability, taxonomic accuracy and ethical practice, and advocate the careful curation and archiving of high-quality datasets in permanent repositories. By promoting best practice in freshwater fish monitoring, this work aims to deepen our understanding of the forces shaping these vital ecosystems and to strengthen their conservation in the face of rapid environmental change.

This paper provides an overview and detailed methodology for assessing the qualitative and quantitative status of fish populations in lakes and reservoirs. It provides a comprehensive account of field procedures and initial data processing. Key sampling approaches, multi-mesh gillnets, hydroacoustic surveys, beach seining and boat-based electrofishing, are described in the context of the EU Water Framework Directive for assessing the ecological quality and potential of standing freshwater bodies.

Monitoring generally involves the ongoing assessment, analysis and evaluation of a particular situation or phenomenon. A fundamental requirement of any monitoring programme is that its results remain comparable over time and space. In the context of fish monitoring, this means that data must be consistent across different water bodies and survey years (Kubečka & Soukalová, 2022; Kubečka et al., 2022a). Ensuring such consistency requires that all monitoring surveys follow standardised procedures (Bonar et al., 2009). The European Committee for Standardisation (CEN) has been instrumental in this effort by developing pan-European standards for fish sampling applicable to all types of water bodies (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

This publication was originally driven by the AMISEPT project (Application of new Bio-Socioeconomic Models for Fish Farming in Tunisian Dam Reservoirs), funded by the Institution for Agricultural Research and Higher Education (IRESA). One of the outputs of the project is an updated methodology for monitoring fish stocks in lakes and reservoirs, aimed at improving the water quality of dam reservoirs. The present paper builds on previous European guidelines for fish sampling by Kubečka and Prchalová (2006), Kubečka et al. (2010) and Kubečka et al. (2022a), which have so far only been applied within Europe. We therefore present a new edition that not only reviews the European methodologies but also adapts them for the first time to Tunisian reservoirs (North Africa). By sharing our field experience, together with insights from the wider literature, we hope to provide valuable guidance to scientific communities beyond Europe. Depending on its objectives, fish monitoring in lakes and reservoirs can be carried out at different levels:

- According to the Water Framework Directive (2000/60/EC), adopted by the European Parliament and Council on 23 October 2000, the assessment of fish communities requires data on species abundance, biomass distribution and population size and age structure. These metrics are essential for determining the ecological status or potential of a water body (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).
- More focused objectives, such as elucidating the drivers of fisheries catches, supporting scientific research, or managing baseline information on fish stocks and their commercial exploitation, require higher resolution data. This involves collecting samples that are more representative of the population and quantifying errors due to gear selectivity and spatial heterogeneity in fish distribution, expressed as known probabilities of estimation error and confidence intervals (Kubečka & Soukalová, 2022).
- Different methods are used to monitor juvenile (age-0 or young-of-the-year) communities. As juveniles are the smallest cohort, sampling strategies need to be adapted accordingly. Estimates of juvenile abundance provide critical information on the strength of individual year classes, a key factor in understanding population dynamics and recruitment success. Because juvenile surveys target a single cohort that can vary significantly from year to year (Jůza et al., 2014), they are generally excluded from routine monitoring of older fish, which covers multiple year classes in a single effort. Although juveniles may occasionally appear as bycatch in whole community surveys (Prchalová et al., 2009b), dedicated juvenile sampling is not usually considered a core component of multi-cohort fish monitoring programs (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

The European standard EN 14962 "Water Quality- Guidance on the scope and selection of fish sampling methods" (CEN, 2005) provides the overarching framework for the selection of appropriate sampling techniques (Kubečka & Soukalová, 2022; Kubečka et al., 2022a). Below, three other CEN documents routinely inform the monitoring of fish communities under the Water Framework Directive:

- EN 14757 (2015 update) for multi-mesh gillnet sampling,
- EN 15910 (2014) for mobile hydroacoustic estimation of fish abundance,
- EN 14011 (2003) for electrofishing.

Among the international adaptations for standing water monitoring, the Scandinavian (Appelberg et al., 1995), Austrian (Gassner et al., 2006) and German (Mehner et al., 2005; García et al., 2006) schemes have been used. This review is intended to complement these European guidelines and standards.

Well-designed monitoring programs should provide data on fish numbers, biomass, species composition and size (and age) structure throughout a water body or its major subdivisions. If either the water body or its fish assemblages are heterogeneous, spatial variation in these metrics must be explicitly considered (Kubečka & Soukalová, 2022; Kubečka et al., 2022a). Such heterogeneity typically manifests itself along three main spatial gradients:

- Vertical (depth) gradients, driven by light penetration, temperature stratification and oxygen levels;
- Longitudinal gradients, particularly in valley reservoirs and elongated lakes;
- Transverse gradients, distinguishing benthic (near-bottom) from pelagic (open-water) habitats (Kubečka & Soukalová, 2022).

Gradients determine which parts of a water body are used as sampling habitats, ideally, zones where the fish community is fairly uniform and any variation between samples is largely random. Selecting suitable habitats is a crucial preparatory step for any survey. Gillnets are the only gear capable of sampling all habitat types; all other methods exhibit some degree of habitat selectivity, which must be taken into account when extrapolating results to the whole water body (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

If it is possible to sample all habitats but their proportional areas differ, three main analytical strategies can be applied:

- Relative indices for specific habitats: Calculate indices separately for habitat categories (benthic vs. pelagic). This approach does not provide metrics for the whole water body, but reflects the data limitations of methods that cannot cover all habitats (such as hydroacoustics, seining or electrofishing) (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).
- Stratification of effort by habitat volume: Distribute sampling effort so that the number of nets in each habitat reflects its proportion of the total volume of the water body. Whole-lake values for species composition, abundance and biomass are then obtained by averaging over all catches. The European Gillnet Standard (CEN, 2015) provides detailed guidance on depth-stratified benthic sampling, although achieving proportional sampling in extensive pelagic zones can be challenging when pelagic volume greatly exceeds benthic volume (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).
- Volume-weighted averaging: Weight fish parameters from each habitat by the volume of that habitat (Lauridsen et al., 2008; Kubečka et al., 2013; Alexander et al., 2015; Tesfaye et al., 2022). This is the only viable method for deriving lake-wide population metrics in large water bodies (area > 1 km^2, depth > 10 m) (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

In water bodies that can be completely drained, fish stocks can be assessed either by using the procedure described below or by carrying out a complete inventory through exhaustive fishing when the reservoir or pond is emptied. Such total catches provide data on total abundance, biomass and species composition. Drainable ponds often contain both valuable commercial species and undesirable "weedy" fish. To obtain an accurate stock estimate, non-commercial species must also be accounted for. This is done by analysing their proportion in the commercial catch, by monitoring individuals passing through screens during water discharge, and by inspecting the pond bottom after fishing (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Sampling strategies

Fish species and size classes in lakes and reservoirs are not uniformly distributed, but show spatial density gradients that should be at least partially understood to generate reliable data (Prchalová et al., 2008b). As different sampling gears cover different areas, and it is usually impractical to sample an entire water body, especially larger ones, a site-based design can be used for spatially restricted methods (gillnets, shore electrofishing and beach seines). Sampling sites should be selected to capture the main spatial gradients in fish distribution and to represent all depth zones in proportion to their occurrence (a depth-stratified design). Although these guidelines focus on the use of gillnets, other gear types can be used at the same sites using the same site-based approach (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

The number and arrangement of sampling sites depend on the size, volume and shape of the water body. At each site, multiple benthic and pelagic gillnets should be deployed across all habitat types, following a depth-stratified scheme. In elongated systems such as reservoirs with distinct tributary and dam zones, at least two sites, one in the inflow region and one near the dam, are recommended (Kubečka & Soukalová, 2022). Fish abundance, biomass and species richness typically peak in the inflow regions of such systems (Prchalová et al., 2008b, 2009a; Vašek et al., 2016). For reservoirs larger than 150 ha, a third site in the central basin should be added; for reservoirs larger than 500 ha, a fourth site halfway between the tributary and central zones is advisable. In addition, each bay covering more than 10% of the total area warrants its sampling site (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

A continuous sampling approach applies uniform effort along straight transects of the lake, making it well suited to techniques where gear deployment is complicated and time-consuming, such as pelagic twin trawls (Riha et al., 2012), and impractical to repeatedly disassemble and reassemble during a survey. Typical examples are pelagic twin trawls (Riha et al., 2012; Rakowitz et al., 2012) or standard trawls (Jůza & Kubečka, 2007; Jůza et al., 2015). Furthermore, the lower frame of pelagic trawls is not designed for rough bottom contact, so sampling must follow a roughly straight path in the deeper parts of the lake (Kubečka & Soukalová, 2022). In contrast to small fry trawls, these larger nets are rarely used for routine long-term monitoring of fish communities in most countries.

In comparison, a whole-lake survey strategy, systematically covering every part of the water body, is the most comprehensive method, capturing the full range of environmental gradients. Common implementations include zigzag hydroacoustic surveys or depth-stratified gillnet sampling (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Period and method selection

Fish catch rates are linked to the metabolic activity of the fish, which in the case of ectothermic species is determined by the ambient water temperature. Therefore, scheduling sampling during periods when the majority of target species are active, namely during the growing season, when ecosystem productivity is at its peak, yields the most representative catch (Kubečka & Soukalová, 2022; Mili et al., 2021). In lentic systems, it is optimal to conduct surveys during the warm months. It is advisable to avoid periods when reproductive behaviour (increased activity and spawning migrations) significantly changes the distribution and activity of species, as well as periods when fish retreat to deeper zones for hibernation (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

The European standard EN 14962 (CEN, 2005) provides overarching guidance on the selection of appropriate fish sampling techniques, with the choice influenced by the type of water body, the monitoring objectives, the need for data comparability and other situational factors. An effective monitoring programme aims to characterise the true composition of the fish assemblage using minimally selective methods (Kubečka et al., 2009), thereby avoiding significant over- or under-representation of key species, while overcoming the challenge of quantifying absolute density per unit area or volume. In practice, hydroacoustic methods and multi-mesh gillnets are often used in large-scale surveys of lakes and reservoirs (Kubečka & Soukalová, 2022; Mili et al., 2021; Kubečka et al., 2022a). Although hydroacoustics can approximate fish biomass, its main limitations are the lack of taxonomic resolution of acoustic data and reduced accuracy in surface and near-bottom blind zones (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Gillnets can effectively sample almost all standing water habitats, but their catches are dependent on fish activity and provide only relative measures of abundance and biomass. Their passive nature can lead to significant under- or over-representation of certain species (Kubečka & Soukalová, 2022; Mili et al., 2021). Active techniques - such as electrofishing and seining - provide more quantitative and reliable estimates, but are limited to shallow areas. Trawling and seining perform well in open water (Riha et al., 2012), but their technical complexity has prevented them from becoming standard tools in routine fish monitoring (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

No single method provides a complete, unbiased snapshot of a fish community under all conditions. Therefore, a combination of sampling methods remains the most effective way to collect robust data on fish assemblages in lakes and reservoirs. By understanding the limitations of each method and exploiting their complementarities, researchers can move closer to truly quantitative assessments (Kubečka & Soukalová, 2022; Mili et al., 2021). When logistical or practical constraints force the use of semi-quantitative or selective techniques, it is important to remember that the observed community structure may differ from reality. Nevertheless, these approaches can be valuable for monitoring changes in specific size classes of target species, provided that the chosen method provides consistent, repeatable samples (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Catch and Data Processing

All of the sampling methods outlined, except hydroacoustic surveys, result in a physical fish catch that serves as our environmental sample. Each entire catch is immediately processed to extract the ichthyological information needed for analyses of species composition, abundance (both relative and absolute), biomass, and size or age structure (Kubečka & Soukalová, 2022; Mili et al., 2021). To ensure data quality, fish are handled and measured as soon as possible after capture. Individuals older than one year are sorted by species and measured (standard length) to the nearest 5 mm, while juvenile gillnet bycatch is measured to the nearest 1 mm (Kubečka & Soukalová, 2022; Kubečka et al., 2022a). For each specimen, its species and length are recorded in field protocols, which also record catch metadata, such as water body, date, site coordinates, habitat type, net configuration and other relevant environmental details (Kubečka & Soukalová, 2022; Mili et al., 2021; Kubečka et al., 2022a).

Age Analysis

We remove otoliths and scales from a representative subset of individuals (100 fish per abundant species, covering the full size range) to estimate age, although other calcified structures may also be used (Vander-Kooy, 2009). Otoliths are our primary choice for age determination in these samples. For species with large *Sagitta*, such as zander and members of the family Mugilidae, we specifically use the *Sagitta*, whereas for cyprinids with smaller *Sagitta*, we prefer the lapillus (Stevenson & Campana, 1992). If young cyprinid species (e.g. rudd or roach) have well-defined scale rings, we collect scales from the left flank, just above the lateral line and approximately above the base of the pelvic fins (Jůza, 2003). Following Kubečka and Soukalová (2022), all scales and otoliths are stored in paper envelopes and thoroughly air-dried to prevent deterioration. Each sample bag is labelled with the date, water body, sampling location and habitat, species name, standard and total length, weight and, if possible, sex of the fish. In addition, material collected for age analysis may also be used to assess length-weight relationships (Kubečka & Soukalová, 2022; Mili et al., 2021; Kubečka et al., 2022a).

Length-weight relationships and biomass

A minimum of 100 individuals per focal species should be weighed to the nearest gram to derive the length-weight relationship. Specimens should be selected to cover the full range of sizes encountered to ensure that the resulting model applies to all size classes (Kubečka & Soukalová, 2022; Mili et al., 2021; Kubečka et al., 2022a). This relationship is most commonly expressed by the power function:

$$W = a^*L^b$$

where (W) is the weight of the fish, (L) is its length, and (a) and (b) are parameters estimated from the data. As the value of \(a\) depends on the units used for (W) and (L) (grams vs. kilograms or millimeters vs. centimeters), while (b) remains constant, it is important to always report the units for both weight and length (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Once the parameters (a) and (b) are determined, they can be used to estimate the weight of each captured fish without weighing each fish in the field. The sum of these estimated weights gives the total biomass of the catch, which can be further broken down by species or size group. If insufficient sample sizes or other constraints prevent the calculation of site-specific length/weight ratios, it is acceptable to use ratios derived from other waters or those listed for each species in FishBase, provided that the source of the ratio is clearly stated in the results (Kubečka & Soukalová, 2022; Kubečka et al., 2022a).

Sampling by gillnets

Gillnets are passive fishing tools whose effectiveness depends entirely on the movement of fish through the gear (Prchalovå & Kubečka, 2022). Fish become entangled in a gillnet by being gilled, wedged or caught by their teeth or other body parts (Hamley, 1980; Prchalovà et al., 2008a). A typical gillnet consists of the mesh panel itself, a weighted lead line at the bottom, a buoyant float line at the top, and lateral side lines (Prchalovå & Kubečka, 2022; Mili et al., 2015). These components are carefully balanced so that the net hangs vertically in the water with its meshes fully open. Gillnets are most commonly deployed as either bottom-set (benthic) or mid-water (pelagic) multi-mesh configurations (Prchalovå & Kubečka, 2022; Mili et al., 2015). Standardised sampling using benthic and pelagic multimesh gillnets follows the European standard EN 14757 'Water Quality-Sampling of fish with multimesh gillnets (CEN EN14757, 2015), and the protocols outlined here are taken directly from this standard while reflecting current best practice (Prchalovå & Kubečka, 2022; Kubečka et al., 2022a).

Gillnet sampling has several important advantages:

- It allows sampling in all depth layers of a water body, thus covering all habitat types present in a reservoir.
- It can capture a wide range of fish species.
- It efficiently samples a wide size range of fish (specimens larger than 40 mm are retained by standard multi-mesh nets; Prchalovå et al., 2009b), and the geometric progression of mesh sizes ensures that the size distribution of the catch closely reflects that of the resident population (Kurkilahti, 1999). This makes gillnet data a reliable basis for assessing size structure and estimating age distributions (Prchalovå & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a).

Gillnet sampling is compliant with the EU Water Framework Directive (2000/60/EC) and is now adopted as a standardised fish sampling technique in most EU Member States and Tunisia. Results obtained with multi-mesh gillnets are highly comparable to those reported in international studies (Prchalovå & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a). However, several limitations of gillnet sampling should be considered:

- Gillnets provide catch-per-unit-effort (CPUE) estimates of relative abundance and biomass, but the conversion between CPUE and absolute density or total biomass (individuals or weight per hectare or cubic meter) remains poorly resolved.
- In areas with submerged obstacles such as fallen trees, stumps, snags or rocks, gillnets are susceptible to significant damage.
- Only actively moving fish are vulnerable to capture, which can lead to under-representation of certain species, size classes or sexes in the sample (Kurkilahti et al., 2002; Olin & Malinen, 2003; Prchalovå et al., 2008a, 2009b; Zak et al., 2018; Prchalovå & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a). Conversely, some groups may appear over-represented, a bias that can be mitigated by adjusting species or size class proportions.
- Catchability varies with body morphology, size and swimming ability. For example, eels are rarely caught in gillnets (Vetemaa et al., 2006; Prchalovå et al., 2013a), as is the European catfish *Silurus glanis* (Prchalovå & Kubečka, 2022; Mili et al., 2021).
- Net saturation or avoidance may occur: fish already entangled in the net reduce the probability of further capture, especially in dense populations, necessitating saturation correction factors (Olin et al., 2004; Prchalovå et al., 2013b).
- When left overnight, gillnets generally cause mortality. Although in some cases live fish, typically larger predatory individuals, can be carefully disentangled and released, this process is time-consuming and not feasible for smaller specimens (Prchalovå & Kubečka, 2022; Kubečka et al., 2022a).

Equipment

Standard gillnets are constructed from 2.5-metre panels of uniform mesh size sewn together over their full height. A typical multi-mesh gillnet consists of consecutive panels: 5, 6.25, 8, 10, 12.5, 15.5, 18, 19.5, 24, 28, 35, 40 and 55 mm knot to knot. Although the order of these panels was originally randomised, it was later standardised for all nets.

- Benthic gillnets are 1.5 m high (covering 45 m^2) and weighted so that the lead line rests on the substrate while the float line maintains a vertical profile; they are deployed in at least 1.6 m of water to sample bottom habitats and are equipped with end-of-line float lines to facilitate retrieval (Prchalovå & Kubečka, 2022). In contrast, pelagic gillnets, usually 6 m high, are used to sample the water column.
- Epipelagic variants are 3 m high (reducible to 1.5 m in shallow systems such as tributaries and ponds), cover 90 m^2 (or 45 m^2 in shallow water nets) and require a minimum depth of 5 m (3 m in shallow areas) to sample surface waters (Prchalovå & Kubečka, 2022). This design conforms to the European standard EN 14757 "Water Quality-Sampling of fish with multi-mesh gillnets" (CEN 14757, 2015). Depending on their buoyancy and configuration, gillnets can be classified as either benthic or pelagic, depending on the habitat they target.
- Mesopelagic gillnets are suspended at intermediate depths between the surface and the bottom using a combination of slowly sinking lead lines and floats arranged along a string of the desired length. Each net is 3 m high and covers an area of 90 m^2. These nets target mid-water pelagic zones and must be set in waters at least 8 m deep (Prchalovå & Kubečka, 2022).
- Bathypelagic gillnets have the same construction as epipelagic nets, but are positioned above the lake or sea bed using weighted line segments. They also cover an area of 90 m^2 and are used to sample deeper pelagic habitats. Although a minimum depth of 10 m is recommended, the exact depth may vary from site to site (Prchalovå & Kubečka, 2022).

Large-mesh gillnets are added to the standard mesh series to catch larger fish (> 30 cm standard length) typical of lentic systems. Additional mesh sizes of 70, 80, 90, 110 and 135mm (knot to knot) have been shown to improve the representation of species such as common carp (*Cyprinus carpio*), European eel (*Anguilla anguilla*) and wels catfish (*Silurus glanis*), which are underrepresented in standard nets alone (Prchalová et al., 2009b; Smejkal et al., 2015; Mili et al., 2015; Kubečka et al., 2022a).

Each panel of mesh size is 10 m long. The 70, 80 and 90 mm panels can be made of monofilament, while the 110 and 135 mm panels perform better when made of multi-filament or multi-strand materials, provided they meet the following breaking strength requirements: 8-14 kg for 110 mm mesh and 14-20 kg for 135 mm mesh (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

Deployment: Large-mesh nets follow the same deployment protocols as standard gillnets. They can be attached directly to standard nets for ease of deployment. Plastic rings can be attached to the mesh intersections to reduce corner entanglement (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

Data handling: Catch data from large-mesh nets must be analysed separately from data from standard nets. Combining them would compromise comparability with historical datasets or results from other sites using only standardised gillnets (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

In addition to the nets themselves, the following equipment is recommended for optimal gillnet sampling:

- A motorised boat with spare oars;
- A depth finder (e.g. an entry-level commercial echosounder);
- Ropes, floats, and anchors for setting pelagic nets;
- Sturdy containers or boxes to hold both empty nets and those with catches during transport;
- A supply of anaesthetics (or alternative means) and tagging tools to safely immobilise and identify fish during retrieval;

- A GPS unit and detailed location map to mark net positions;
- Buckets and additional vessels to hold samples before and after processing;
- Precision scales and measuring weights to document individual fish size and mass;
- Standardised data sheets or templates to record each haul;
- Brightly coloured buoys (yellow) to increase net visibility in areas with boat traffic.

Sampling Protocol

- *Selection of sampling sites*

Gillnets can be deployed in almost any location within a water body, except for areas immediately adjacent to dams or water intake towers, heavily trafficked docks and harbours, recreational areas, or areas where submerged obstructions (fallen trees, stumps, rocks) are present (Prchalovå & Kubečka, 2022; Mili et al., 2021). During sampling, gillnets are usually set according to either a site-specific or whole-lake survey design and can be set vertically at multiple depth horizons as well as longitudinally along the lake axis to capture the full vertical and longitudinal distribution of fish (Prchalovå et al., 2008b, 2009a; Prchalovå & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a).

The habitat is classified as either benthic or pelagic, and a depth-stratified random sampling scheme is recommended at each station: within each depth stratum, net sets are randomly placed. The number of strata corresponds to the maximum depth of the site, and the sampling effort in each stratum is proportional to its water volume. Deeper strata occupy a smaller volume and thus receive fewer net sets. A detailed allocation of effort by depth can be found in Annexe A of the European standard EN 14757 "Water Quality-Sampling of fish with multi-mesh gillnets" (CEN EN 14757, 2015).

The total number of gillnets required will depend on the size and morphology of the lake. In waters with relatively uniform shorelines, with no distinct bays, tributaries or impoundments, benthic nets will be randomly deployed, while pelagic nets will target the deepest parts of the basin (mining lakes). In more complex systems with pronounced tributary and reservoir zones, at least two sampling sites should be established in each of these areas (Prchalovå & Kubečka, 2022; Kubečka et al., 2022a), as fish abundance, biomass, and species richness often peak in tributary inflows (Prchalovå et al., 2008b, 2009a; Vašek et al., 2016; Prchalovå & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a). For water bodies larger than 150 ha, three sites (tributary, mid-lake, reservoir) are sampled; for those larger than 500 ha, an additional site is placed between the tributary and mid-lake zones. Bays covering more than 10% of the lake area are also included. Special attention is given to elongated reservoirs where riverine and lacustrine waters meet, forming an ecotonal transition between two different habitat types (Prchalovå & Kubečka, 2022; Kubečka et al., 2022a). This ecotone comprises two distinct habitat types:

- A slow-flowing section of river with reduced current, typically cooler temperatures in summer, and minimal or no phytoplankton and zooplankton. Due to the shallow depth, only benthic gillnets can be used, as pelagic nets are not suitable (Prchalová & Kubečka, 2022).
- A tributary-fed section of the reservoir, located downstream of the plunge point, where the cooler water of the tributary sinks below the warmer epilimnion of the reservoir. This area supports both zooplankton and phytoplankton, and both benthic and pelagic gillnets can be used depending on water depth (Prchalová & Kubečka, 2022).

The immersion point is often identified by surface debris that marks where the river water sinks. It is advisable to compare the sampling design of the tributary with the water temperature depth profile. The most upstream gillnets in the true reservoir should not be positioned immediately downstream of the plunge point, as the river water requires some distance to fully submerge below the epilimnion. If temperature or depth profiles are not available, upstream gillnets should be set at least 200 meters downstream of the plunge point. In particular, fish catches in the slowed river habitat are typically much lower than those in the tributary-fed reservoir section, so it is important to report these habitats separately (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

For fish abundance monitoring studies, the minimum sampling effort for gillnets must ensure a level of precision that allows the detection of a 50% difference in CPUE between sampling events (CEN EN14757, 2015). This required effort is determined by the surface area and maximum depth of the water body. Currently, the European standard only specifies sampling effort for benthic gillnets (Prchalová & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a). To address this limitation, we also established minimum effort guidelines for pelagic gillnet sampling. Although increasing sampling effort generally improves precision, it is possible to reduce effort while still obtaining reliable estimates of key fish community metrics, thereby minimising unnecessary fish mortality (Prchalová & Kubečka, 2022). The three most effective reduced-effort strategies include sampling the entire longitudinal profile within the epilimnetic or near-surface layers and sampling all depth strata at key points along the longitudinal axis, particularly near dams and tributaries (Blabolil et al., 2017). Furthermore, deploying only one gillnet per depth stratum and location usually does not compromise the accuracy of fish community indicators (Blabolil et al., 2021; Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

- *Sampling*

Gillnets are deployed from a boat in a straight line either to a specific depth or, in the case of benthic gillnets, within a target depth range. Depth is determined using a depth finder, typically a simple echosounder with a beam angle of up to 20 degrees. Epipelagic and mesopelagic gillnets must be secured to a stable structure, such as a bridge abutment, navigation buoy or shoreline tree, to prevent drift. The exact location of each gillnet is recorded with a GPS device and may also be manually recorded on a map. Nets are usually set 2 to 3 hours before sunset and retrieved 2 to 3 hours after sunrise. During the summer, gillnets are set no later than 19:00 and must remain in place until at least 7:00. This timing corresponds to the peaks of fish activity, which typically occur at dusk and dawn (Prchalová et al., 2010; Prchalová & Kubečka, 2022; Kubečka et al., 2022a). By setting nets during this period, both peaks are captured, thus minimising sampling bias. If overnight deployment is not possible, a shorter exposure period may be used (Prchalová & Kubečka, 2022). Situations requiring shorter exposure may include water management issues, time constraints, very high fish densities leading to net saturation, or the need to keep captured fish alive. However, catches from shortened sets must be standardised to overnight levels. Shortened sets must last at least two hours and should overlap with either the evening or morning peak of fish activity. Exclusively nighttime deployments are discouraged because fish catchability decreases significantly during the night, leading to biased and inefficient sampling (Prchalová et al., 2010; Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

It is strongly recommended that gillnets be carefully organised in boxes to avoid entanglement during deployment. Wind and weather conditions can be severe when setting gillnets, and dealing with a tangled net is an experience best avoided. Once the exposure period is over and the gillnet is returned to the box with the catch, it must be accurately labelled with details such as habitat, location, depth and other relevant gillnet-specific information (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

Benthic sampling typically requires two people: one to operate the gillnets and another to monitor and adjust the depth. In the case of pelagic gillnets, which are higher than benthic nets, two handlers are also ideal. For meso- and bathypelagic nets, a third person is recommended to manage the ropes connecting the floats to the net, if available (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

Catch evaluation

Gillnet sampling primarily provides information on species composition, abundance, biomass, and size and age distribution of fish populations (Prchalová & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a). Species composition is assessed by aggregating data across all sampled habitats. For reservoirs with an elongated shape, it is advisable to weight species composition by the proportion of the total reservoir volume that each site and depth layer represents (Tesfaye et al., 2022). However, this adjustment is not necessary for waters with a more uniform shape. Relative abundance is measured as catch per unit effort (CPUE), based on the number of fish caught per 1000 m^2 of gillnet deployed overnight, both within each habitat and overall. Biomass per unit effort (BPUE) is calculated in the same way. Reporting catch data for individual nets is generally less reliable unless net dimensions are also provided, as nets may vary in size. Results are usually presented separately for juveniles and adults (Prchalová & Kubečka, 2022; Mili et al., 2021; Kubečka et al., 2022a).

Corrections of Gillnet Catches

As a sampling technique, gillnet monitoring is inherently biased due to different types of catch selectivity. Fish caught with gillnets typically represent an unknown fraction of the size classes or species present in the studied water body (Prchalová & Kubečka, 2022; Mili et al., 2021). Gillnet selectivity refers to the qualitative representation of this fraction, often illustrated by the probability of catching certain size classes or species. Whenever corrections are applied, the procedure must be thoroughly described in the methods section (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

- *Mesh Size Selectivity*

Considerable effort has been devoted to understanding the proportion of fish caught by each gillnet mesh size. A geometric series of mesh sizes with a coefficient of 1.25 helps to cover a wide range of fish sizes while maintaining relatively uniform selectivity within a given size interval (Prchalová &

Kubečka, 2022; Mili et al., 2021). However, research conducted since the 1990s by Prchalová and Kubečka (2022) has shown that each mesh size has its selectivity curve. Consequently, the SELECT statistical model was developed to account for selectivity differences between mesh sizes (Millar, 1992, 2000; Millar and Holst, 1997). To use the SELECT model, catches must be organised by mesh size. Given the complexity of mesh size correction, it is recommended to use specialised software incorporating the SELECT model rather than attempting manual corrections (Prchalová & Kubečka, 2022; Kubečka et al., 2022a).

- *Correction for gillnet saturation*

Fish already caught in gillnets may reduce the chances of catching additional fish, a phenomenon known as saturation or avoidance (Olin et al., 2004; Prchalová et al., 2013b). Saturation is influenced by the fish density in the sampled water body (Prchalová & Kubečka, 2022). When comparing gillnet catches in water bodies with different fish densities, saturation at higher densities may introduce bias. To mitigate this, a detailed model of gillnet catches was developed (Prchalová et al., 2011). This model approaches gillnet catches not as CPUE, but as the biomass of fish that can be caught per hour using an empty gillnet with fish of unit activity (catchable biomass rate). This approach eliminates the confounding effects of saturation, variations in fish activity, and fish escaping from the nets during exposure (Prchalová & Kubečka, 2022).

The catchable biomass model is rather complicated to use manually. To simplify its application, a conversion table was developed that allows users to determine catchable biomass values based on absolute catches obtained with standard benthic gillnets (45 m^2 sampling effort) (Prchalová & Kubečka, 2022). To standardise catches to a uniform gillnet effort (1000 m^2), the following formula is used: $E_{1000} = E_{45} \times 1000/45$, where E_{1000} is the catch per 1000 m^2 of gillnet and E_{45} is the raw, unstandardised catch relative to effort. Here, 1000 and 45 refer to the respective net areas used for effort standardisation (Prchalová & Kubečka, 2022).

- *Correction for shortened exposure time*

If it is necessary to shorten the exposure time from overnight to a shorter period, this adjustment must be clearly stated when reporting the results (Prchalová & Kubečka, 2022). In addition, the data should be standardised to reflect the total overnight exposure to ensure comparability between different water bodies. The catchable biomass model presented in the previous section allows for this adjustment (Prchalová & Kubečka, 2022). Using this model, it is possible to convert catches recorded during four different shortened exposure periods: 2 hours around the peak of fish activity at dusk or dawn, 5 hours consisting of the 2-hour peak plus 3 additional hours, 8 hours including the 2-hour peak plus 6 additional hours, and 11 hours consisting of the 2-hour peak plus 9 additional hours (Prchalová & Kubečka, 2022).

Hydroacoustic surveys

Hydroacoustic surveying has become a robust, non-invasive technique that leaves fish behaviour unaltered. It offers rapid, detailed assessments across broad spatial scales and avoids biases associated with site accessibility, fish availability and catchability.

In a typical hydroacoustic survey, scientific echosounders traverse the water, often following pre-designed transect lines in a mobile survey to estimate fish abundance, biomass, size and spatial distribution. Most operations use frequencies between 70 and 200 kHz (although lower and higher bands are also used) because, in temperate freshwater conditions, these mid-range frequencies propagate reliably up to about 100 m from the vessel and can detect targets as small as fish larvae. Each echosounder has a precisely defined sampling volume: it emits short acoustic pulses, "pings" that form discrete pulse volumes (PVS) travelling through the water at about 1,500 m/s. Modern systems automatically correct for minor sound-speed variations due to temperature and salinity. When a ping strikes a fish or other object, some energy is reflected and detected by the transducer, and the total backscatter is displayed as an amplitude echogram. Post-processing relies on a single echo detector (SED) to disentangle echoes from individual fish. If two or more fish occupy the same PV simultaneously, their echoes merge and appear as a single, larger target, making size estimates impossible. The SED separates these multi-target echoes to retain only single fish echoes within each PV. Its output lists each detected fish with attributes including acoustic size, detection time, range and, when using split-beam echosounders, their angular position in the beam. Acoustic size can be expressed as the backscatter cross-section (δ_{bs}, in m^2) or as target strength (TS, in dB re 2π). TS is ideal for visualisation on SED echograms and for plotting size distributions, while the linear δ_{bs} is suitable for quantitative operations such as averaging. The two are related by the standard equation (Kubečka et al., 2022b):

The target strength (TS) and the linear backscattering cross section δ_{bs} are related by:

$$\mathbf{TS} = 10\log_{10}(\delta_{bs}) \quad \longleftrightarrow \quad \delta_{bs} = 10^{\mathrm{TS}/10}$$

When dealing with a distribution of fish sizes, the mean backscatter cross section is calculated as the arithmetic mean of all individual detections:

$$\bar{\delta}_{bs} = \frac{1}{N}\sum_{n=1}^{N}\delta_{bs,n}$$

where (N) is the total number of fish echoes.

Another fundamental quantity derived from echosounder data is the volume backscatter strength S_v (in dB) and its linear equivalent, the volume backscatter coefficient s_v (in m^2/m^3). This coefficient expresses the fraction of the incident sound energy that is returned by a unit volume of water. To estimate s_v, the operator outlines a region of interest on the echogram; s_v is then calculated as the total backscatter from all fish within that volume divided by the enclosed volume of water. The logarithmic and linear forms relate according to:

$$S_v = 10\log_{10}(s_v) \quad \longleftrightarrow \quad s_v = 10^{S_v/10}$$

Similarly, the area backscatter, S_A (m^2/ha), is defined in the same way as S_v, but normalised over an area rather than a volume.

Fish abundance in numbers per cubic metre can be estimated using the scaling method of Balk and Lindem (2014):

$$\text{Abundance (fish/m}^3\text{)} = \frac{s_v}{\delta_{bs}}$$

Here, upper-case symbols denote logarithmic quantities and lower-case symbols denote their linear equivalents. Volume-based abundances can then be converted to fish per hectare.

Hydroacoustic surveys offer several advantages over traditional sampling methods, including high spatial resolution, non-invasive sampling and the ability to cover large areas quickly:

- They allow rapid sampling of large volumes and areas of water, providing a holistic view of the aquatic environment.
- They cause minimal disturbance to fish, ensuring no injury or mortality.
- With no gear selectivity and a high detection threshold (all individuals >2-3 cm in open water), they count virtually all fish above this size.
- By recording geographical coordinates (longitude and latitude) together with time stamps, they provide multi-dimensional data ideal for studying habitat preferences and migration patterns.

In addition, these authors have identified some limitations of hydroacoustic surveys, such as:

- Species cannot be directly identified from acoustic recordings.
- Fish near the bottom, along the shore or in shelters may not be detected.

- Size estimates show greater variability than measurements from captured specimens, especially in horizontal mobile surveys.
- The technique requires sophisticated equipment, specialised expertise and considerable time to process large acoustic data sets.
- Data interpretation can be confounded by factors such as gas bubbles, turbidity caused by flooding, thermal stratification, dense vegetation and the presence of aquatic invertebrates.

Equipment

Scientific split-beam echosounders as the SIMRAD EK 60, remain the workhorses for emitting short, constant wavelength (CW) pulses at the frequencies mentioned above. For horizontal surveys, transducers with low side-lobe levels (≤30 dB) are preferred to minimise off-axis echoes. For vertical sampling in shallow water (<10 m), it's advantageous to use the widest possible beam (practically up to 18° on split-beam systems) to maximise coverage, while in very dense or deep fish aggregations a narrower beam may help resolve individual targets more effectively (Kubečka et al., 2022b).

The newer EK80 broadband echosounder can transmit both CW and frequency modulated (FM) pulses, but as FM acquisition and processing protocols are still being refined, FM mode is not yet used in routine surveys (Kubečka et al., 2022a, b). A complete survey setup also requires:

- A motorised vessel with at least partial shelter to house the electronic equipment;
- An inclinometer to monitor the transducer's inclination;
- A pan-measuring device to track the angle between the transducer's horizontal axis and the vessel's course;
- A deck-operated rotator to maintain proper transducer orientation;
- A laptop with a 12 V DC power supply;
- Calibration spheres (Simmonds & MacLennan, 2005);

- A USB-enabled GPS unit and mapping software loaded with bathymetric charts;
- Paper 'blind' maps for manual backup of field logs;
- Hydroacoustic processing software (Sonar5-Pro, Echoview) (Kubečka et al., 2022b).

Sampling

When carrying out a hydroacoustic survey in a water body where there are no previous acoustic data, it is essential to carry out both day and night echosounding using horizontal and vertical transducers. Such surveys should be postponed if extreme weather conditions (storms, heavy rainfall or strong winds) are forecast, as these conditions not only pose safety risks but also increase background noise in the recordings (Kubečka et al., 2022b). At the other extreme, perfectly calm conditions can also be problematic, as a mirror-smooth surface can distort echoes from targets in the upper water column, leading to ambiguity in both their apparent size and location (Balk et al., 2017; Kubečka et al., 2022a, b).

Horizontal and vertical measurements can be taken simultaneously, either with two separate echosounders or a single instrument equipped with multiplexed transducers, or sequentially, by completing the horizontal transect first and then the vertical. The horizontal transducer should be at least 0.5-1 m below the surface, tilted downwards by about 1-3° (common with 7° beams) to avoid the beam grazing the surface. For vertical profiling, the transducer is mounted about 20 cm below the waterline with the beam pointing straight down (Kubečka et al., 2022a, b).

The overall sensitivity of the echosounder must be calibrated using a tungsten carbide calibration sphere (33.2 mm diameter for 120 kHz; 21.2 mm for 400 kHz; Simmonds and MacLennan, 2005). Modern software on instruments such as the SIMRAD ER60 and ER80 typically includes automated routines to simplify sensitivity adjustments. If a full calibration procedure cannot be carried out, at least the sphere should be recorded on the beam axis and the system gain adjusted until the measured target strength matches the theoretical value (Kubečka et al., 2022a, b).

Short acoustic pulses (0.1-0.5 ms) are recommended for data collection when surveying dense fish aggregations at ranges less than 50 m, whereas longer, higher energy pulses may be preferred for longer ranges. The emission frequency (5-20 pulses per second) should be set according to the maximum distance of the sampled volume: higher repetition rates are only possible after echoes from the farthest bottom or opposite bank have returned (in horizontal mode) or after residual energy between the transducer face and the bottom has decayed (in vertical mode) (Kubečka et al., 2022b). Unprocessed echo returns over the full relevant range (up to 50 m where depth permits) must be stored directly on the control computer hard drive, together with simultaneous GPS tracking of the vessel (Kubečka et al., 2022a, b).

In the case of the Tunisian reservoirs, a split-beam echosounder uses an elliptical horizontal transducer (4° × 10° at -3 dB) to insonify the surface layer (0-3 m depth) and a circular vertical transducer (7° at -3 dB) to sample from 3 m to the bottom. Settings include a pulse length of 0.256 ms, 500 W transmit power and a rate of 10 pings per second achieved by alternating between the two transducers (fast multiplexing at 5 pings/s per channel). For reservoirs shallower than 10 m, the analysis is limited to the horizontal beam only (Laouar & Djemali, 2017).

When designing the survey track, the vessel should follow a zigzag course in wide water bodies, while in narrow or shallow areas it should cover as much of the available space as possible to approximate continuous sampling. The track should be recorded by GPS using GIS-compatible mapping software and sketched by hand on a blank map, noting the time at each waypoint. To ensure adequate coverage, at least 10% of the total volume should be insonified for reservoirs up to 150 ha, and at least 5% for larger systems (Kubečka et al., 2002a, b).

The degree of coverage (Dc) for each survey, calculated according to Aglen (1983), must exceed the recommended threshold of 2 (Godlewska et al. 2009).

For horizontal surveys, the usable range of data (the distance from the transducer) may be limited if strong thermal stratification in the water column causes refraction of the acoustic beam. To mitigate this, temperature profiles should be recorded at a minimum of three points along the longitudinal axis of the water body (Kubečka et al. 2022a, b). Horizontal sampling is typically carried out at a depth of 4 m, corresponding to the epilimnion or its upper part, and this value must be entered into the processing software. Deeper layers are then sampled using vertical beams, whose range ends when the acoustic beams reach the bottom (Kubečka et al. 2022a, b).

Each zigzag transect serves as an elementary sampling distance unit (ESDU; Jolly & Hampton 1990). Mean density and biomass for each reservoir layer are calculated as the weighted average of the ESDU-specific estimates (Djemali et al., 2010; Sokal & Rohlf, 1981):

$$\bar{x}_p = \frac{\sum_{i=1}^{n} B_i A_{si}}{\sum_{i=1}^{n} A_{si}}$$

where xp is the weighted mean biomass (or density), n is the number of ESDUS in the zone, B_i is the biomass (or density) in the ESDU i, and A_{si} is the sampled area of the transect i. Total fish biomass and density for the whole water column are obtained by summing the surface and deep contributions over all ESDUS (Kubečka & Wittingerova, 1998).

Processing and Results Interpretation

Sonar5-Pro (Balk & Lindem, 2006) remains the preferred software for processing freshwater hydroacoustic data sets, as it supports both horizontal and vertical survey modes. Raw acoustic recordings are imported into Sonar5-Pro using the appropriate calibration constants (Kubečka et al., 2022a, b).

In Tunisian inland waters, fish density is calculated using the echo-counting approach. Single-echo detection (SED) is characterised by a relative pulse width between 0.6 and 1.8, a one-way beam compensation of 3 dB and a maximum phase deviation of 8.3°. Each echo must be detected at least twice; no more than two detections may be lost in succession, and the vertical displacement between successive detections must not exceed 30 cm.

The user must delimit the part of the echogram to be analysed, excluding and either manually or automatically masking, bottom returns, opposite shoreline, macrophytes and other non-fish structures. Djemali and Laouar (2017) found that over 80% of the diel acoustic traces in late autumn were upward sloping, likely corresponding to methane bubbles rather than fish (Anderson & Martinez, 2015); therefore, only non-sloping targets are classified as fish.

In vertical surveys, the mean acoustic size of the fish assemblage is derived directly from individual target TS measurements using Love's (1971) backscatter equation. For horizontal surveys, the pooled length-TS relationship published by Frouzová et al. (2005) is applied. A TS threshold of -70 dB is typically used to filter out small echoes at the noise level. Simultaneous gillnet catches provide the length-weight parameters ($W = a\,L_T^{\ b}$).

Combined horizontal and vertical hydroacoustic sampling provides: Sampled water volume; Acoustic size distribution; TS values of individual fish; Fish abundance (ind/ha or ind/m^3); Fish biomass (kg/ha or kg/m^3).

Electrofishing

This section outlines the electrofishing methodology, including a description of the equipment, its application, and the processing and evaluation of the catch. The procedure focuses on the sampling of predominantly older than young fish in still waters, extending previously established methods (EN 75 7706 CEN, 2003; Kubečka & Prchalová, 2006; Bednář et al., 2013; Blabolil et al., 2022). In shallow zones, electrofishing can occasionally be carried out by wading or from the shore, although such opportunities are rare in reservoirs and lakes (Blabolil et al., 2022). Electrofishing has several advantages (Blabolil et al., 2022; Kubečka et al., 2022a):

- It allows sampling along all types of shorelines that are typically inaccessible to nets, such as areas with stumps, roots, aquatic and flooded terrestrial vegetation, submerged trees and large rocks. When properly set and operated, electrofishing is one of the least harmful capture techniques, with fish often recovering quickly and surviving after measurement, while leaving the aquatic habitat undisturbed.
- It allows rapid and efficient sampling of large sections of shoreline, with equipment that is easy to transport and set up; it requires relatively few personnel (3-5 people), and the physical demands and exposure to pollution are minimal; it captures a wide range of fish species and size classes, and can confirm the presence of species that might otherwise be missed (Blabolil et al., 2022).

However, electrofishing also has certain limitations (Blabolil et al., 2022; Kubečka et al., 2022a):

- Its effectiveness decreases in waters deeper than one meter; its efficiency is reduced at low water conductivity, while high conductivity requires more power; high turbidity can make it difficult to detect and retrieve stunned fish; the method can exhibit selectivity by species and fish size, depending on the settings used.
- There is a potential risk of electrocution if safety protocols are not followed, requiring special training and certification for operators. Electrofishing activities must be authorised by appropriate exemptions. Equipment must be meticulously maintained, including regular cleaning, proper storage in dry conditions, and annual inspections by qualified technicians (Blabolil et al., 2022; Kubečka et al., 2022a).

Principles and use of electric fishing

Electrofishing uses an electrical device to create an electric field in the water between two submerged electrodes: a positive (capturing) anode and a negative cathode. The current flow between these electrodes is carried by ions dissolved in the water (Blaboli et al., 2022). Fish within the influence of this electric field experience stimulation of their nervous system. Fish at the edge of the field typically try to escape (excitation), while those closer to the centre tend to orient their heads towards the anode (positive electrotropism) and swim involuntarily towards it (galvanotaxis). Fish may become temporarily immobilised or anaesthetised, often leading to sinking (galvanonarcosis). If a fish reorients itself within the field, it becomes easier to capture (Blaboli et al., 2022; Kubečka et al., 2022a).

In lakes and reservoirs, two main approaches to electrofishing from a boat are used: continuous transect sampling and point sampling at specific locations. Continuous transect sampling is best suited to areas with unstructured or lightly structured shorelines, and can also be used to some extent in open waters or shallow, thermally stratified zones. In contrast, point sampling is preferred in structurally complex littoral areas where continuous sampling would often be interrupted (Blaboli et al., 2022; Kubečka et al., 2022a).

Electrofishing should be avoided in extreme temperature conditions. The optimum water temperature for most fish species is between 10°C and 20°C (Beaumont et al., 2002). The time of day when sampling takes place can have a significant effect on results (Blaboli et al., 2022).

In general, electrofishing at night is less favourable due to reduced visibility and safety concerns. However, reduced fish escape responses at night, together with the shoreward migration of some species from deeper habitats, may be advantageous (Blaboli et al., 2022; Kubečka et al., 2022a).

Equipment

A stable boat of sufficient size should be used to transport electrical equipment, store and process catch and accommodate the crew. The boat must be easy to manoeuvre to avoid obstacles in a rugged coastal environment. In practice, a boat with a length of 5-6 meters and a width of 1.5-2 meters is considered ideal (Blaboli et al., 2022). The size of the boat depends on the number of fishermen, ensuring both their safety and the manoeuvrability of the boat. It can be made of conductive aluminium alloy or non-conductive materials. It may also have two enclosed chambers: one at the bow (for buoyancy) and one at the stern (which can be filled with water to balance the boat, including the bow and barrels). Alternatively, a tilting bow design could be used to bring fishermen closer to the surface (Blaboli et al., 2022). The front of the boat should always include a removable safety railing of at least 1 meter in height, which serves both as a support for the crew and as protection against accidental falls into the water. The boat should also have brackets for an outboard motor at the stern and brackets for paddles in front of and behind the seat. The outboard motor should have a minimum power of 10 kw if the water body to be sampled is large and long distances have to be covered between lake sites (Blaboli et al., 2022; Kubečka et al., 2022a). For electrofishing, the length of the motor leg must be chosen optimally to ensure that the motor cooling water inlet does not rise above the water level when the front of the boat is loaded with a standing crew or a full water tank. The engine leg should be short or adjustable, with the option of a shallow drive (Blaboli et al, 2022). The placement of the catchers and their equipment should be carefully determined and maintained on board. The generator unit is housed in a metal frame and consists of an engine, a power generator, and a control box. Battery-powered systems are usually not feasible due to insufficient power. The generator for an electric boat should have a minimum power of 5 kw, and for fishing in waters with increased water conductivity, at least 10 kw (Blaboli et al., 2022). The control box should be equipped with the possibility of regulating the output voltage for waters with different conductivities so that the total power applied to the water is similar regardless of its conductivity. It should be possible to choose between direct current and pulsed direct current operation. With pulsed current, control of the pulse frequency is an essential component (20 to 100 per second), and individual adjustment of the duty cycle can be provided. The control box should also include a built-in Voltmeter and Amperemeter for orientation control of voltage and current output values (Blaboli et al., 2022; Kubečka et al., 2022a). The operator should be positioned at the front of the boat with a water tank and oxygen or aeration equipment nearby. A water pump may be useful for changing the water in the livewell. The electrical unit should be located at the rear of the boat so that it can be operated by the driver during the trip. In the event of imminent danger to the crew or others, the driver can switch off the unit, and one or two anodes should be installed, depending on the fishing method. Typically, two anodes are mounted in the lower corners of the railing (boom), with one handheld anode available for operation. All equipment must be securely fastened to prevent falling into the water (Blaboli et al., 2022; Kubečka et al., 2022a).

To activate the current, the electric boat is equipped with a dual safety switch system: the main switch on the generator, which has an on/off position, and a foot or hand switch that activates the electrodes only when held in place (dead man's system). The main switch is usually operated by the crew leader (boat driver), while the dead man's switch is operated by the fishing operation leader. Both switches must be operated simultaneously to activate the electric field. A light indicator should indicate the current operating status of the device (Blaboli et al., 2022; Kubečka et al., 2022a).

For continuous fishing with electric boots, a system with two anodes and one cathode is used. The anodes are mounted on 3-metre-long non-conducting rods, which are positioned almost in front of the boat. These rods are fitted with metal rings at the ends to which pins are attached to connect the anodes. The star-shaped anode (0.8 meters in diameter) has six steel cables that are submerged in the water during fishing. Each cable has a diameter of 0.5-1 cm and a minimum length of 0.9 meters (Blaboli et al., 2022). The distance between the centers of the anodes (the tips of the two poles) is approximately 2 meters (Miranda & Kratochvil, 2008). Both poles are independently adjusted in height (tilt level) by lengthening or shortening the chains. If the boat has to travel long distances, it is recommended to raise both anodes above the water. The anode system can be easily dismantled for transport or storage. In point sampling, the anode consists of a non-conductive fishing rod fitted with a metal plate (copper or aluminium alloy) or a conductive frame to which a dip net can be attached (Blaboli et al., 2022; Kubečka et al., 2022a).

The entire hull of an aluminium boat can act as a cathode. Alternatively, a conductive metal strip (copper) with cables immersed in water or the metal hull of a boat can act as a cathode. All conductive components of the boat, including the outboard motor and the metal structure of the electrical system, must be at the same electrical potential as the hull of the boat to prevent accidental penetration of the circuit by stray currents. Copper tape loosely trailing behind the boat or attached to a float is not ideal as it can become entangled in underwater obstacles (such as branches, submerged plants and large rocks), alter the shape of the electrical field or potentially contact the hull or propeller (Blaboli et al., 2022; Kubečka et al., 2022a). According to these authors, the following additional equipment is necessary:

- Safety gear for fishermen (non-conductive waterproof gloves and boots, life jacket, ear protection);
- Instruments for measuring water properties (conductometer, Secchi disk, thermometer);
- Landing nets (dipnets) with handles made of non-conductive materials (2-3 m long), preferably with knotless netting. The mesh size and depth of the net should be appropriate to the size of the target fish. Double-frame landing nets are recommended as the mesh sewn to the inner frame is less likely to be damaged by friction with the bottom (Blaboli et al., 2022; Kubečka et al., 2022a).
- A GPS device to measure the length of the fishing section and to locate the transect;
- A blank map of the water body to record the presence of different coastal environments in different areas;
- Measuring tools, scales, protocols and stationery; - Sufficient lighting to catch and process fish at night;
- A communication device (mobile phone or walkie-talkie) for safety purposes;
- A voltmeter/oscilloscope for mapping and checking electrical field parameters;

- Sufficient lighting for catching and processing fish when fishing at night;
- A communication device (mobile phone or walkie-talkie) for safety purposes;
- A first aid kit and a powder fire extinguisher;
- Tools for assembling electrical components into a compact unit (Blaboli et al., 2022).

Sampling

When sampling a water body for the first time or following visible changes since the last sampling (e.g. water level fluctuations or flooding), it is essential to select suitable sites at each site in advance. These sites should be representative of the local area and cover a significant proportion of the riparian structure of the water body (boulders, rocks, beaches, submerged trees, terrestrial or aquatic vegetation). The number, type and placement of electrofishing sites should be consistent with the specific objectives of the sampling and depend on the morphology and size of the water body. In most cases, the number and location of these sites will correspond to those required for gillnet sampling (Blaboli et al., 2022; Kubečka et al., 2022a).

For each site, key characteristics such as bank slope, bottom substrate and presence or absence of vegetation should be documented. The location should be recorded using a GPS device and also plotted on a map of the water body. It is strongly recommended that photographs be taken to enable the habitat conditions to be reproduced at a later date. Information on sampling location, time and site conditions should also be recorded in the logbook (Blaboli et al., 2022; Kubečka et al., 2022a).

Before starting sampling, the equipment should be checked for correct operation and adjustments made outside the actual sampling area (at a site that will not be part of the survey). It is advisable to familiarise yourself with the conditions at the sampling site, such as water temperature, transparency and conductivity. Based on these conditions, the appropriate fishing method should be chosen and the settings of the electrical equipment (voltage, type of current and, for pulsed DC, pulse frequency or duty cycle) adjusted accordingly (Blaboli et al., 2022). Where conditions permit, the most fish-friendly DC should be used. If pulsed DC is necessary (due to high water conductivity or low power), the lowest possible pulse frequency should be used. If more than 20% of the fish escape, the frequency should be increased gradually. Setting the frequency too high initially can cause fish to become stunted (galvanonarcosis) and unable to move towards the anode (galvanotaxis). Sinusoidal alternating current is harmful to fish and is prohibited in most cases (Blaboli et al., 2022; Kubečka et al., 2022a).

Before starting sampling, it is important to secure the selected area. Unauthorised persons are not allowed near the site or its immediate vicinity. The safety zone extends at least 10 meters from the electric boat. All equipment and electrode connections must be inspected before sampling. Electrodes should be placed in the water before operating the equipment. Before sampling, the crew must agree on the sampling method, communication signals and the responsibilities of each operator. Special care should be taken when fishing at night (Blaboli et al., 2022; Kubečka et al., 2022a).

When fishing with an electric boat, the boat moves slowly in a straight line, either parallel to the shore or in open water. The minimum distance from the shore depends on its slope. Electrofishing in systematic transects is only feasible in large, shallow areas with water depths of around 1 meter. Experience suggests that the minimum fishing effort should cover at least 100 meters of shoreline, with a minimum catch of 100 fish older than the juveniles of the year. In waters with low fish densities, a shoreline length of 1000 meters is considered sufficient, even if the 100 fish requirement is not met. Even in areas of high fish density, it is important to design the catch to ensure that the sample is representative, with minimal variability between catches (Blaboli et al., 2022).

The boat is propelled by a low-speed motor, allowing the boat to move at a speed that allows the crew to effectively collect stunned fish. Typically, the boat travels at speeds between 0.5 and 3 km/h, depending on fish density, rugged shorelines and obstacles in the water. Fishing is generally conducted only once at each sampling site (Blaboli et al., 2022; Kubečka et al., 2022a).

During continuous sampling, the foot switch is usually activated by an operator positioned at the bow. For safety reasons, the main switch is operated by the driver at the stern, who has a clear view of the entire crew and can switch off the power if necessary. The power can be switched on continuously or, preferably, every 3-5 meters along the boat's path, with short pauses of about 1-3 seconds. Briefly turning off the power helps to reduce the likelihood of fish being stunned at the edge of the electric field, thereby improving their capture within the field (Blaboli et al., 2022; Kubečka et al., 2022a). Stunned fish are collected by two operators at the bow. Fish must be immediately removed from the electric field and placed in a tank of well-oxygenated water to facilitate recovery. If fish densities are high, additional crew members may be required to assist in catching fish that the primary operators cannot reach (Blaboli et al., 2022; Kubečka et al., 2022a).

For point sampling, the boat follows the shoreline, and at intervals, the anode is lowered into the water in front of the boat (0.2 to 1 m deep) while an electric current is activated for 5 to 10 seconds (Kratochvil et al., 2014; Blaboli et al., 2022; Kubečka et al., 2022a). The boat is then stopped, and all stunned fish are collected in a marked container. The boat then moves to the next point, which is at least 5 meters away. Because of the short distances between points, the boat is usually moved by rowing or poling. By positioning the anode away from structured substrates (dense vegetation, boulders), the fisherman can use galvanotaxis to attract fish from these environments that might be missed by continuous electrofishing (e.g. bitterling, sunfish, topmouth gudgeon). The number of sampling points is recorded in the logbook (Blaboli et al., 2022; Kubečka et al., 2022a).

Electrofishing efficiency

Electrofishing efficiency refers to the proportion of the community sampled. This efficiency is influenced by several factors, some of which may vary depending on the site and sampling period. Factors influencing electrofishing efficiency include biological characteristics, environmental conditions, technical aspects of the electrofishing equipment and the experience of the crew (Blaboli et al., 2022; Kubečka et al., 2022a).

- *Biological factors*

Biological factors are influenced by fish species (including anatomical, morphological and physiological characteristics) or size (Dolan & Miranda, 2003; Blaboli et al., 2022). Larger fish are more likely to escape the electric field due to their greater kinetic energy. However, they also have a higher potential difference between their head and tail and are more visible in the water compared to smaller fish, both of which lead to size selectivity. In addition, a higher pulse frequency should be used to target smaller fish (Blaboli et al., 2022; Kubečka et al., 2022a).

Fish behaviour is another important factor in the success of electrofishing. Spawning fish tend to be less cautious and show a delayed reaction to an approaching electrofishing boat. Males, in particular, remain at spawning sites longer and are therefore more likely to be captured (Smejkal et al., 2022; Blaboli et al., 2022). Fish seeking shelter may become stuck in shelters after being stunned, which could lead to an underestimation of the catch. In addition, electrofishing is generally less effective at capturing bottom-associated species (Hupfeld et al., 2022; Blaboli et al., 2022; Kubečka et al., 2022a).

- *Environmental factors*

Factors affecting the success of electrofishing include the environmental conditions during sampling, such as water conductivity, which is determined by ion concentration and temperature. Ion concentration is influenced by several factors including geology, precipitation and run-off in river basins. Conductivity decreases at lower temperatures because ions become less mobile, leading to higher resistivity (Blaboli et al., 2022; Kubečka et al., 2022a). A 1°C drop in temperature can reduce conductivity by 2.5%. With increased resistance, more power is required to increase electrical voltage and current. In areas of low conductivity, it is advisable to use larger electrodes, especially the anode, while in areas of high conductivity, the electrode surface area should be reduced and the voltage lowered (Blaboli et al., 2022; Kubečka et al., 2022a).

The substrate of the bed and bank also plays a critical role in the propagation of the electric field. If the substrate has a high conductivity (e.g. clay, organic sediments, mud), the field can be weakened as the current moves through it. Conversely, substrates with low conductivity (gravel, stones) allow the electric field to spread more effectively in the water, making it easier to catch fish. Electrical equipment should be adapted to the type of substrate and bottom structure. Areas with metal objects on the bottom should be avoided (Blaboli et al., 2022; Kubečka et al., 2022a).

Turbidity is another important factor in electrofishing. In turbid waters, electrofishing has the advantage of making it more difficult for fish to detect approaching fishing boats. However, the disadvantage is the reduced visibility of stunned fish (Blaboli et al., 2022; Kubečka et al., 2022a).

- *Technical factors*

DC or pulsed DC with different waveforms are commonly used for fish sampling. In high-conductivity waters, if the power of the unit is insufficient, even when using pulsed current, the current requirement can be reduced by adjusting the pulse frequency accordingly. This adjustment makes the process less stressful for the fish without compromising the efficiency of electrofishing. The correct pulse frequency can attract fish from a greater distance. When electrofishing, the frequency should be set in a range that is safe for the fish (20-30 Hz). If the efficiency of electrofishing is insufficient, the pulse frequency should be gradually increased in steps of about 10 Hz (Blaboli et al., 2022; Kubečka et al., 2022a).

The size and shape of the electrodes affect the range and intensity of the electric field (Martinez & Kolz, 2013; Blaboli et al., 2022). However, the electric field should not be too strong near the anodes to avoid harming the fish. It is recommended to minimise energy losses by making the cathode area significantly larger than the anode area. The electric field is not uniform; it is strongest at the electrodes and typically has little effect beyond about 10 meters. Electrodes with a larger surface area offer less resistance as the current flows into the water, creating a larger and less intense electric field near the electrode, reducing the risk of injury to fish. In waters with low conductivity, larger electrode surfaces are required to ensure sufficient current delivery to the water (Blaboli et al., 2022; Kubečka et al., 2022a).

Catch and Data Processing

After sampling in a particular environment and location, the equipment must be switched off, the anodes removed from the water, and the boat securely anchored to the shore. The catch should then be processed as quickly as possible. Fish that are more sensitive to handling, particularly predators, should be processed first. In addition, larger fish should be processed first because they consume more oxygen, making them more vulnerable to low oxygen levels (Kubečka et al., 2022a). Fish older than the young of the year are identified by species, weighed, and their standard length measured. Fish up to 100 mm are measured to the nearest millimetre, while larger fish are measured to the nearest 5 mm. Weighing may be used to determine age or to back-calculate growth, after which the fish are released (Blaboli et al., 2022). All data are recorded in a protocol, including information on the environment (locations and water bodies) from which the samples were collected. Fish should be released near the shore at the sampling site, at a sufficient distance from areas where further fishing will take place. The water in the tank should be replaced with fresh water before the next sampling (Blaboli et al., 2022; Kubečka et al., 2022a).

Semi-quantitative catch data provide information on relative abundance and biomass, species composition, size and age structure, and year-class strength. The number and biomass of fish caught by electrofishing are expressed per unit effort. Three basic effort measures are used to interpret continuous electrofishing catches. The abundance of fish caught refers to the length of shoreline sampled (number of fish per 100 meters of shoreline). Catch per 100 meters of shoreline can be reported separately for each environment or location, as well as for the whole water body. Alternatively, catch can be related to sampling time (Blaboli et al., 2022).

Most commonly, catch is converted to the number of fish caught per fishing hour. In any case, sampling should last at least 10-15 minutes, depending on the number of fish caught. It is also possible to convert the catch to a fishing area, e.g. the length of the bank multiplied by the width of the sampled section. This method is not widely used because of the difficulty in quantifying the total area sampled (Blaboli et al., 2022; Kubečka et al., 2022a).

For point sampling, at least 10 electrofishing points should be used if fish are caught, or a total of 30 points per habitat/location if no fish are caught at some points. Catches are reported as the average number of fish per point and the percentage of points with catches. The length of the coastline is less representative for point-based sampling than for continuous sampling, as the distance between sampling points often affects fish density. Standardisation of catch per area can be derived from the circumference of the anode, but this method is not commonly used in continuous electrofishing (Blaboli et al., 2022; Kubečka et al., 2022a).

Observing fish that do not swim in a convulsive or jerky manner indicates that the unit is not properly adjusted. With proper adjustment, fish are generally not stunned, and if they are, unconsciousness lasts only a short time. Fish usually recover fully within a few minutes (Blaboli et al., 2022). In extreme cases, such as improper use of electrical equipment and excessive exposure to electric current, physiological exhaustion or complete paralysis (tetanus) of the fish may occur. This can lead to irreversible damage due to muscle tension and, in severe cases, spinal fractures (Culver & Chick, 2015; Blaboli et al., 2022). In addition, contact with the active electrode can cause burns on the surface of the fish (Blaboli et al., 2022; Kubečka et al., 2022a).

- *Work safety*

Safety is of paramount importance when working with electricity in aquatic environments. The use of electrical equipment can pose significant risks to life and requires that individuals be adequately trained. The sampling team should consist of at least three fishermen who have undergone professional training over three years (Blaboli et al., 2022). During this training, they must demonstrate their ability to operate electrical equipment and administer first aid, and be certified upon completion. Each year, the electrical equipment should be professionally inspected by an electrician, and any defects found should be repaired. All fishermen in the team must wear life jackets, non-conductive waterproof boots and gloves. Sampling is prohibited in poor visibility or adverse weather conditions (such as rain, storm, frost or extreme heat). A fire extinguisher must be available on the boat in the event of a fire. Additional local health and safety regulations may apply depending on the country (Blaboli et al., 2022; Kubečka et al., 2022a).

Sampling by beach seine nets

Beach seining is an active fishing technique used to catch fish in shallow coastal areas. This method is one of the oldest forms of net fishing, dating back thousands of years (Gabriel et al., 2005; Ennouri et al., 2015). Its longevity can be attributed to the simplicity of the equipment and its ease of use. The net consists of a fence with floats at the top and weights at the bottom, often supplemented by hauling ropes at the sides. Over time, this technique has evolved into several other fishing methods, including purse seines and trawls (Wardle, 1993; Riha & Kubečka, 2022; Kubečka et al., 2022a).

Today, beach seines are used in a variety of aquatic environments, such as reservoirs, lakes, rivers and coastal marine areas, for both commercial fisheries and fish community sampling. The design and application of beach seines vary widely depending on the target species, their size, or the specific environment in which the technique is used (Hahn et al., 2007; Riha & Kubečka, 2022; Kubečka et al., 2022a). This discussion focuses specifically on the use of beach seines for qualitative and quantitative sampling of littoral species in still waters. In this context, the recommended net and sampling design has a low size and species selectivity, providing a representative overview of the littoral fish community (Riha & Kubečka, 2022). The use of beach seines for sampling has several advantages (Kubečka et al., 2022a):

- The equipment used is simple and inexpensive;
- A large littoral zone can be surveyed in a relatively short time;
- The sampled area can be clearly defined, allowing accurate calculations of its extent and description of environmental features within it (such as bottom slope and substrate, and the presence of submerged macrophytes);
- Sampling is active and can be carried out at any time of day;
- The range of species and sizes that can be captured is broad, although the method allows selectivity in species and size;
- Fish are captured alive with minimal damage (Riha & Kubečka, 2022).

However, there are several disadvantages associated with the use of beach seines:

- The technique is restricted to shallow littoral zones, typically to a depth of 4-5 meters;
- The bottom of the sampled area must meet certain conditions: a shallow slope of no more than 25°, flat terrain, no large obstacles such as rocks, stumps or dense submerged macrophyte cover, and no thick layer of soft sediment;
- The sampled areas may not accurately represent the entire shoreline of the water body (Riha & Kubečka, 2022).

Equipment

A beach seine is a type of net fence, often equipped with a central bag that widens in the middle. This bag serves as a collection area where fish accumulate during a tow, limiting their ability to escape (Hahn et al., 2007;

Riha & Kubečka, 2022; Kubečka et al., 2022a). The net is encircled by a rope (the line), with the lower line (lead line) weighted and the upper line (float line) equipped with floats. The design of the net depends on the method of deployment. For the most accurate sampling, the net can be used as a block net, surrounding a sample area. Alternatively, the net can be deployed parallel to the shore and hauled in with ropes, provided the net is long enough to minimise selectivity in sampling (Riha & Kubečka, 2022; Kubečka et al., 2022a).

Riha and Kubečka (2022) propose specifications for seine nets. The recommended length is 150 to 200 meters for the block net method or at least 40 meters for the trawl method. The height of the net should be between 4 and 5 meters, and the mesh size should be 10 mm to prevent the escape of smaller fish (these meshes are small enough to retain fish 1+ years old or older of most species). Smaller meshes can increase drag and trap more debris and silt. However, if the target fish can pass through the 10mm mesh, then the mesh size should be adjusted accordingly. A 200 g/m weighted line should be sewn along the bottom of the net to provide a load. The floats should be made of polystyrene and placed no more than 1 meter apart on the top line (Kubečka et al., 2022a). When designing block nets, it is recommended that floats be colour coded every 5 to 10 meters using two easily distinguishable colours to facilitate identification of the length of net deployed when it is released into the water (Riha & Kubečka, 2022; Kubečka et al., 2022a).

Additional equipment is required (Kubečka et al., 2022a):

- A rowing boat with a minimum load capacity of 500-800 kg and a length of 4-5 meters is recommended for sampling. This boat should be equipped with oars for mobility during net deployment and an outboard motor for faster transport between sampling sites.
- A depth gauge or a small commercial echo sounder;
- A GPS device to record the exact location of sampling sites and the dimensions of the area swept;

- Equipment for measuring and weighing fish, together with logbooks to record catches and other necessary tools for collecting fish samples;
- A repair kit for the net in case of damage, which should include thicker thread and a larger needle;
- Sampling should involve at least four people (Riha & Kubečka, 2022).

Sampling

The selectivity of beach seines is mainly influenced by the type of bottom at the sampling sites. When the bottom is suitable (with a gentle slope, unstructured substrate and no obstructions), the efficiency of the technique can be close to 100% if applied correctly. However, this efficiency decreases if optimal conditions are not maintained (Pierce et al., 1990; Riha & Kubečka, 2022; Kubečka et al., 2022a). Benthic fish species are often underestimated when the bottom consists of large rocks or small irregularities (Lyons, 1986; Parsley et al., 1989). Similarly, all species tend to be underestimated when the net becomes entangled on submerged obstacles and is either released or rolled up due to the dense presence of macrophytes (Pierce et al., 1990; Riha & Kubečka, 2022). The efficiency of the net can also be reduced by higher flow velocities, especially near tributaries (Neufeld et al., 2016; Kubečka et al., 2022a). In addition, the length of the net used plays an important role in sampling efficiency. Size selectivity is inversely related to net length, as larger fish can escape when shorter nets are used (Riha et al., 2008; Riha & Kubečka, 2022). It is therefore advisable to change sampling locations and increase net length if large numbers of escaped fish are observed. In addition, hauls with significant problems, such as net snagging or bottom rope rolling, should be excluded from the results. The use of longer nets, especially those longer than 40 meters, is also recommended when using the pull-by-rope method, as this may reduce size selectivity (Riha et al., 2008; Riha & Kubečka, 2022; Kubečka et al., 2022a).

Sampling can be conducted at any time of day, but numerous studies have shown that nighttime sampling is more effective for quantitative assessment of fish populations (Midwood et al., 2016; Riha et al., 2015; Wegscheider et al., 2020). At night, fish are less affected by sampling equipment (Wardle, 1993; Riha et al., 2008; Rakowitz et al., 2012) and their distribution is more uniform and less patchy, as fish schools and aggregations typically disperse at night (Riha et al., 2017). In addition, fish densities and species richness are generally higher due to inshore migration during the night (Kubečka, 1993; Riha et al., 2011, 2015). Night sampling should take place approximately one hour after sunset and 1.5 hours before sunrise to avoid migration peaks at dusk (Prchalová et al., 2010). Sampling should not take place on clear full moon nights with strong moonlight or during nights with weather disturbances (e.g. heavy rain, storms). The optimal time of year for an unbiased assessment of fish stocks varies by location, but should be outside the spawning season for most species, as spawning can lead to aggregations that affect sampling results (Riha & Kubečka, 2022; Kubečka et al., 2022a).

In general, site-specific sampling strategies should be applied when selecting sampling sites. Suitable areas for seining typically represent only a small part of the littoral zones, making site selection a challenge (Kubečka et al., 2022a). However, as sampling success is highly dependent on the selection of an appropriate littoral site, great attention must be paid to this aspect (Riha & Kubečka, 2022).

The sampling area should have the following characteristics: a gentle slope (maximum 25°), absence of obstacles (such as stones larger than 20 cm, branches, tree stumps, etc.), no significant irregularities in the terrain and limited presence of submersed macrophytes (≤ 3 kg/m^2) (Pierce et al., 1990; Riha & Kubečka, 2022). It is advisable to inspect unfamiliar areas before sampling. These areas can be inspected using a thick rope (left for at least 6 hours before sampling), and if the rope does not snag, a seine sample can be taken. Alternatively, the bottom can be visually inspected by divers (Riha & Kubečka, 2022; Kubečka et al., 2022a).

In addition, it is recommended that 2 to 3 samples be taken at each site selected for gillnetting. This will help to assess sampling variability at each site and increase the representativeness of the results. These hauls should be taken at different locations within the sites. However, if two suitable locations for netting are not available, all hauls may be conducted on an adjacent beach (Riha & Kubečka, 2022; Kubečka et al., 2022a).

Manoeuvring beach seine nets

Sampling begins with the preparation of the net. The net is folded at the front of the boat, ensuring that the top line is folded on one side and the bottom line is folded on the opposite side. These two lines mustn't be crossed to avoid difficulties in deploying the net. In addition, any debris (such as twigs, wires or fish) caught in the net should be removed before loading, as they can cause the net layers to stick together, resulting in unwanted fish avoidance and distortion (Riha & Kubečka, 2022; Kubečka et al., 2022a).

The net is deployed to enclose the entire swept area. The boat crew usually consists of three people: one person rows, steers the boat and monitors the depth with an echo-sounder, while the other two deploy the net. A fourth person remains on shore to prevent the net from being pulled into the water during deployment (Riha & Kubečka, 2022). The boat moves at a speed of 1-2 km/h, perpendicular to the shore, while the crew releases the net into the water. The boat then follows the side of the swept area, which should be at least 25-30 meters long. However, this length should be adjusted according to the slope of the bottom, as the net can only be deployed to a depth equal to its height (the recommended depth is half a meter less than the height of the net, to avoid the net getting caught when pulled) (Kubečka et al., 2022a). If the bottom depth exceeds the net height within 10 meters of the shore, it is recommended to use a higher net or to choose a location with a shallower slope. When the boat reaches the side end, it turns 90° towards the shore, and the net is deployed in this direction, perpendicular to the shore. If the depth permits, an effort is made to maintain a rectangular or square shape for the enclosed area to simplify the calculation of swept area dimensions (Riha & Kubečka, 2022; Kubečka et al., 2022a).

In this technique, a worker on shore holds the end of the side rope (the side at the top of the folded net) while the boat moves into open water, maintaining an angle of approximately 45-60° to the shore. When the end of the rope is reached (or the maximum depth for deployment is reached), the boat will turn parallel to the shore, and the crew will begin to deploy the net. It is recommended to maintain a similar distance from the shore when deploying the net, provided the bottom depth does not exceed the height of the net. Once the net is fully deployed, the boat turns towards the shore, maintaining the same angle as when the first rope was deployed, and deploys the other rope towards the shore (Riha & Kubečka, 2022; Kubečka et al., 2022a).

After deployment, the workers start pulling the net on both sides towards the shore. During the pulling process, one worker on each side pulls the top line, while two workers on each side pull the bottom line. The bottom line should be pulled approximately 0.5 to 1 meter in front of the top line, but the distance between the lines should not be too great to prevent the top line from sagging. The bottom line must remain in contact with the bottom at all times to prevent fish from passing underneath. The top line should be held as high as possible during the haul, tightening it by shaking and bending it to keep the floats moving and prevent fish from escaping. As the net is pulled, the workers at either end slowly move towards each other until the entire net is out of the water. The catch is then shaken into the section of the net with the most fish and collected in appropriate containers for further processing (Riha & Kubečka, 2022; Kubečka et al., 2022a).

In addition, Riha and Kubečka (2022) state that the ropes should be pulled symmetrically from both sides towards the shore, maintaining an angle of 45-60° to the shore. Both ends of the net should reach the shore at the same time. If one team is faster, they should wait for the slower team on the other side to bring their end of the net ashore. Once both ends of the net have reached the shore, the procedure is the same as for pulling the block net (Kubečka et al., 2022a).

Measurement and calculation

In order to obtain an accurate estimate of fish CPU parameters, it is essential to measure the swept area accurately. Several methods can be used to do this:

- Use of a portable GPS device during deployment to track the trajectory of the boat (after deployment, a worker can also use GPS to record the shape and dimensions of the shoreline within the swept area). This is the most accurate way of estimating the dimensions of the swept area.

- Measure the side lengths of the swept area using a colour-coded marker on the net. Marked floats are counted and recorded along each side of the swept area during deployment, and these records are then used to calculate the side lengths. If the swept area deviates from a regular shape, the shoreline can be measured using a tape measure or other distance-measuring device.

- Use a tape measure or other measuring device to measure the side lengths of the swept area. These devices can be used after the net has been deployed to measure and record the length of each side. This method is more time-consuming than the previous two (Riha & Kubečka, 2022; Kubečka et al., 2022a).

The procedure becomes simpler as the net length is fixed and only two measurements are required: the distance from the shore to the net using GPS, another measuring device or the length of the deployed rope on each side, and the length of the swept shoreline measured using GPS or a measuring device after the haul is completed (Kubečka et al., 2022a).

All dimensions and the approximate shape of the sampled area should be carefully recorded. Ideally, the area sampled should be rectangular or square when using a block net, or trapezoidal when using a pull-by-rope method. However, it is often more common for the area to resemble a trapezoid when following depth isobaths (Kubečka et al., 2022a). As a result, different formulae are required to calculate the swept area depending on its shape. The formulas are as follows:

Rectangle: Sa = a * b / 10,000; square: Sa = a^2 / 10,000; Trapezoid: Sa = (a + l) / 20,000 * b (Riha & Kubečka, 2022).

Where 'Sa' is the area swept (in hectares), 'a' is the length of the coastline swept, 'b' is the distance from the coast to the net, and 'l' is the length of the net (all in metres).

Catch is based on area: catch parameters are divided by the swept area, with the resulting values providing abundance/biomass per hectare (Riha & Kubečka, 2022).

Evaluation of results

Beach seine sampling provides data on the abundance, biomass and size distribution of species found in the nearshore areas of each site at the time of collection. When evaluating the fish community of an entire water body, it is important to recognise that open water and structured habitats support different species and size distributions (Riha et al., 2015; Riha & Kubečka, 2022; Kubečka et al., 2022a). The assessment should take into account the proportion of the coastline that has similar characteristics to the areas sampled by the beach seine, to ensure the representativeness of the data. This factor should also be considered at the sampling design stage. If less than 30% of the coastline is suitable for seine sampling, it is recommended to combine seine sampling with electrofishing or the use of gillnets in areas inaccessible to seines (Riha & Kubečka, 2022; Kubečka et al., 2022a).

Managing and monitoring

As data volumes continue to grow, researchers are seeking improved methods for managing, organising, storing, sharing and ensuring the integrity of data (De Souza and Blabolil, 2022). Effective data documentation is essential to ensure a seamless workflow, while the use of appropriate data management practices is necessary to maintain data accuracy and prevent errors or misinterpretations. The importance of proper data management is increasingly recognised in the scientific community, as data are critical to every phase of scientific research, from experimental design and data collection to analysis and publication. Researchers need to be able to handle large datasets and have access to appropriate tools that allow them to retrieve, evaluate and communicate their findings with other scientists (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Increased generation and use of data in science

As the generation and accumulation of data continues to increase over time, effective management, processing, storage and sharing are becoming critical for long-term studies in ecology and freshwater fisheries (Kubečka et al., 2022a). A key driver of the increasing volume of data in science has been the development of increasingly sophisticated measurement and data collection techniques (De Souza and Blabolil, 2022). Technological advances have enabled scientists to generate and collect data with greater precision and in larger quantities than ever before. In addition, data generation has become a fundamental aspect of scientific research in many fields, and funding and resources are often allocated to support these efforts. Together, these factors have contributed to the exponential growth of data generation observed in modern science, making it a central aspect of knowledge advancement (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

The challenges associated with the growing volume of data in science are common to all disciplines, and ecology and freshwater fisheries are no exception (De Souza and Blabolil, 2022). The ever-increasing amount of data being generated makes storage, management and analysis increasingly difficult and expensive. Awareness of data-related challenges in scientific projects has increased, and issues such as inconsistencies in data generation, organisation, sharing and reproducibility are being addressed more seriously. Inconsistent data management makes it difficult for other scientists to replicate results or build on previous research. While these challenges are significant, they can be overcome with appropriate planning and resources (Kubečka et al., 2022a). With the right infrastructure and skilled personnel, the growing volume of scientific data can be harnessed to accelerate discovery and deepen our understanding of the world. However, this requires the establishment of a robust data management system (De Souza and Blabolil, 2022). There are several methods for storing electronic records, ranging from simple text files or spreadsheets to advanced software solutions. The choice depends on the operating system, the volume of information, its structure and the anticipated needs (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Data management

Data management can be divided into several steps: data digitisation involves receiving data from field and/or laboratory collection protocols; data processing refers to the methods used to format data for database entry. Data validation, which can be performed manually or automatically using specific validation scripts, ensures that all data entries are accurate. Data storage and backup is the process of securely storing data files and creating backups. Meanwhile, data documentation focuses on thoroughly recording all steps involved in handling data and providing clear descriptions that allow new users to easily understand the data (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Each of these steps is essential to ensure that people can find, use and build on data from previous studies. The foundation of data management lies in the careful handling of data. Data must be properly organised and stored to maintain data integrity, which is essential to avoid errors in analysis and interpretation. These steps are usually carried out by specialised personnel, and collaboration between all data professionals is necessary to establish a clear and functional workflow (Kubečka et al., 2022a). Effective communication is essential, as is setting clear, specific expectations for each role in data management. For example, data analysts need access to reliable data, while data entry staff need clear instructions on how to enter data into protocols and databases. Only through coordinated teamwork can scientists ensure that data handling is accurate and efficient. Whether a data analyst or a database administrator, all team members must remain vigilant about data management and communicate effectively with their colleagues. There is little room for error when working with scientific data (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Database

In today's increasingly data-centric world, it is more important than ever to have an effective system for storing and managing data. One of the most widely used and powerful tools for this purpose is a database. A database is a structured collection of data that can be easily accessed, modified and manipulated. There are different types of databases, each with unique features and functions (Kubečka et al., 2022a). In general, database systems are designed either to store and retrieve text-based data, such as articles or records, or to handle numerical data. Within these categories, some database systems specialise in managing large amounts of heterogeneous data, others focus on specific types of data, and some can be tailored to meet a wide range of user needs. Specifically, for scientific research, database systems that focus on organising numerical data are often the best option. These systems allow researchers to efficiently store large amounts of complex data and provide robust query capabilities for quickly retrieving specific values or performing advanced statistical analyses (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

A relational database is a type of data storage system that organises data into tables. Each table is structured around specific fields or categories and can contain different types of data, such as text, numbers, dates or images. Relational databases are highly versatile and can store virtually any type of data, making them a powerful tool for information management (Kubečka et al., 2022a).

Each table in a relational database holds data about a particular type of information, and relationships are used to link two tables within the database (Kubečka et al., 2022a). Relational databases contain two types of keys:

primary keys and foreign keys. A key is a field that uniquely identifies a row in a table. A primary key is a special type of key with additional properties: it must be unique, non-null and fixed. A foreign key is a key used to link two tables, typically defined in one table and referencing a primary key in another. Foreign keys are critical because they enforce referential integrity, ensuring data consistency across multiple tables. Without foreign keys, data could be isolated or lost in the database. They also allow data from multiple tables to be queried (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Various programming languages and specialised software are available for interacting with relational databases. The ideal solution depends on the specific requirements of the database, the data it will store, and the users who will access it. However, some of the most commonly used database management systems include MySQL, Oracle and Microsoft SQL Server (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

SQL, or Structured Query Language, is a programming language developed in the 1970s for interacting with databases. Because of its simplicity and versatility, SQL is widely used in scientific projects. The syntax of SQL is simple and consists of commands that allow various operations to be performed on a database. SQL commands can be used to insert, update or delete data; create or modify database objects such as tables or views; or retrieve data from a database (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

There are several key SQL commands for retrieving data from relational databases. The most commonly used command is SELECT, which allows you to extract specific records based on predefined criteria. Another important command is WHERE, which allows results to be filtered according to specified conditions. In addition, ORDER BY can be used to arrange data in a particular order, while GROUP BY helps to organise records into categories for more efficient analysis. Finally, the JOIN command facilitates the merging of multiple database tables, enabling more complex queries on related records. Taken together, these commands provide the basic framework for database queries and are essential tools for data analysts and database administrators (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Relational database

An example of a freshwater fisheries database would contain data on freshwater fish sampling in reservoirs and lakes across Europe. The database tables would likely include information on: sampling, catch, species, reservoir/lake, location and campaign. These tables would be linked by relationships. For example, the sampling table could be linked to the campaign table, while the catch table could be linked to the species table (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

In this case, the catch table contains data on all fish caught, such as species, length, weight and sex. The sampling table lists the fishing methods used, such as gillnets, trawls and electrofishing (Kubečka et al., 2022a). The locations table lists the locations within the water body, including their names and GPS coordinates. The campaigns table identifies specific fieldwork campaigns, including dates and responsible personnel (De Souza and Blabolil, 2022).

To create an SQL query, the user needs to understand the data in the relevant tables and how they are related (through primary and foreign keys). In this example, the focus is on catch data for fish species in freshwater lakes, with two related tables: one for the taxonomy of different fish species and another for catch data. The user would start the SQL query with the SELECT statement to specify what data they want to extract from each table. For the species table, the user could choose to retrieve rows where `sp_speciesid` corresponds to Northern Pike (Esox lucius). In the second table, which contains catch information, the user can request the weight of the fish and filter the results by matching the `sp_speciesid` for northern pike catches (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

After entering these basic SELECT statements into the query, the user can join the two tables using an appropriate JOIN operator (such as INNER JOIN). This provides a straightforward view of the Northern Pike biomass.

This simple SQL query is an effective way of retrieving data from relational databases (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Data accessibility and legacy

While all scientific fields are experiencing a rapid increase in data production and handling, in certain fields, a lack of programming skills can be a significant barrier for many researchers. However, there are several efficient ways to interact with structured relational databases without having to write code or learn SQL. One approach is to use a data access layer, a software component that acts as an intermediary between the database and the application, allowing researchers to retrieve data without directly writing SQL queries. Another approach is to use tools such as Microsoft Access or Tableau, which allow users to build and modify queries visually. These tools provide an accessible entry point for exploring data without the need for programming skills. In addition, many resources, including books and online materials, are available to help researchers gradually develop their understanding of SQL and effective data querying (Molinaro, 2005; De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Anyone who has tried to manage data knows how challenging it can be to keep up with evolving data storage and processing technologies. As new technologies emerge, older, reliable tools often become obsolete, and while it may be tempting to continue using outdated systems, doing so risks future data loss or corruption (Kubečka et al., 2022a). Valuable datasets can become inaccessible or damaged over time if they are not properly maintained. Therefore, it is crucial to consistently back up data and migrate it to modern storage solutions when necessary. By adopting these proactive practices, scientists can ensure the long-term availability and usability of their data (De Souza and Blabolil, 2022).

As data increasingly underpins scientific research, researchers need to consider how their data will serve future generations. Datasets are invaluable, providing a wealth of information for fields such as ecology and fisheries science. However, the complexity of these datasets can make them difficult for new researchers to interpret and use (Kubečka et al., 2022a). To preserve their value, datasets should be thoroughly documented, including clear descriptions of methods, data sources, and interpretation guidelines. Through careful documentation and organisation, today's researchers can ensure that their datasets remain accessible, understandable, and useful to future scientists (De Souza and Blabolil, 2022; Kubečka et al., 2022a).

Conclusion

In science, data management is critical to advancing research and fostering innovative discoveries. Data underpins every phase of scientific work - from designing experiments and collecting information to analysing results and disseminating findings. By implementing strong data management practices, researchers can organise vast amounts of data, making it easier to retrieve, interpret and share information with the wider scientific community. Ultimately, effective data management fosters greater collaboration and supports the ongoing advancement of research efforts. As such, robust data management is a critical element for today's scientists and will continue to be so in the future. To comply with international standards, researchers are advised to consult EN 14996 (CEN, 2006), which guides how to ensure the quality of biological and ecological assessments in aquatic environments.

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CHAPTER IV

FUTURE DIRECTIONS IN AQUACULTURE RESEARCH: TRENDS AND INNOVATIONS

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Introduction

Aquaculture has become an essential player in ensuring food security worldwide by providing sustainable options to satisfy the increasing need for seafood. This section investigates upcoming research avenues in aquaculture by looking into trends related to sustainability, technological advancements, health management, and socioeconomic effects. The focus is on innovative approaches like Integrated Multi-Trophic Aquaculture (IMTA), models of the circular economy, and the development of sustainable feed. Significant progress in automation, genetic advancements, bioinformatics, and disease control are highlighted as key factors that promote efficiency and resilience within aquaculture systems. Additionally, the significance of community involvement, gender equity, and market forces in facilitating sustainable aquaculture growth is examined. Future studies should incorporate innovations across various disciplines to boost productivity, promote environmental responsibility, and encourage socioeconomic development, establishing aquaculture as a foundational element of global food systems in the 21st century.

Aquaculture is now a crucial industry in the world of food production, playing a vital role in the availability of seafood and aiding people's livelihoods across the globe. With the continuous increase in the global population, the need for sustainable and healthy food sources has grown, placing aquaculture as a key topic in conversations about food security and environmental sustainability (FAO, 2022). This chapter will discuss future pathways for research in aquaculture, highlighting new trends and creative methods that could tackle the obstacles encountered by the sector.

The body of work regarding aquaculture has grown considerably in the last few years, showcasing the changing dynamics of the industry and the urgent demand for sustainable methods. Studies suggest that aquaculture stands as one of the quickest expanding areas in food production, experiencing an annual increase of around 5.3% since the year 2000 (FAO, 2022). This expansion is fueled by multiple elements, such as improvements in breeding methods, efficiency of feed, and management strategies.

Sustainability continues to be an essential issue in the field of aquaculture. The major obstacles endangering the future sustainability of aquaculture systems include overfishing, destruction of habitats, and pollution (Naylor *et al.*, 2021). Integrated Multi-Trophic Aquaculture (IMTA) has surfaced as an effective approach, which enables the production of diverse species within one system, thus improving resource use and decreasing environmental damage (Chopin *et al.*, 2010). Research indicates that IMTA can enhance the recycling of nutrients and lessen the environmental impact of aquaculture practices (Zhang *et al.*, 2022).

The incorporation of technology in fish farming has revolutionized conventional methods. Modern agricultural approaches, which involve sensors and Internet of Things devices, allow for immediate tracking of water conditions, the well-being of fish, and feeding effectiveness. These advancements support decisions based on data, improving both efficiency and environmental responsibility (Bai *et al.*, 2021). In addition, progress in genetic studies, including selective breeding and genome editing, is leading to the creation of aquaculture species that are more durable and effective (Gjedrem & Baranski, 2021).

Disease control presents a major obstacle in the fish farming industry, frequently resulting in significant financial setbacks. Investigating vaccination methods and developing strains with disease resistance is essential for promoting fish welfare and minimizing death rates (Baker *et* *al*., 2020). Furthermore, the contribution of probiotics in boosting intestinal health and resilience against diseases has become notable, with research suggesting that probiotics can enhance growth outcomes and lower the occurrence of infections (Merrifield *et al*., 2010).

The economic and social dimensions of aquaculture are gaining acknowledgment as crucial for sustainable progress. Community-driven aquaculture programs enable local participants and advocate for fair resource allocation (Béné *et al*., 2016). Grasping consumer inclinations and market patterns is equally important for the viability of aquaculture offerings, as shoppers are increasingly conscious of sustainability matters and are seeking seafood that is sourced responsibly (Kumar *et al*., 2022).

The upcoming direction of aquaculture studies is set to tackle the intricate issues related to sustainability, technological advancements, health care practices, and economic considerations. By concentrating on these specific domains, scientists can aid in creating robust aquaculture frameworks that fulfill the increasing worldwide appetite for seafood while reducing adverse effects on the environment.

1.Sustainability in Aquaculture

Sustainability within aquaculture stands as a vital concern, particularly as the industry encounters growing strains from environmental issues, finite resources, and the demand for ethical food creation. Practices that promote sustainable aquaculture seek to reduce ecological footprints while enhancing both productivity and economic sustainability. This segment explores the primary sustainability obstacles and groundbreaking approaches that are influencing the direction of aquaculture moving forward.

1.1 Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture, often referred to as IMTA, represents an innovative method that encourages the farming of various species from different levels of the food web within a unified system. By utilizing the waste created by one species as nourishment for another, IMTA boosts resource utilization while minimizing the ecological impact of aquaculture enterprises.

Studies have shown that IMTA can greatly enhance nutrient recycling, fostering more robust ecosystems and promoting environmentally sound production methods (Chopin *et al.*, 2010; Zhang *et al.*, 2022).

Current research underscores the ability of IMTA to alleviate the adverse effects associated with conventional aquaculture, such as nutrient overloading and habitat destruction. For example, research conducted by Troell *et al.* (2021) revealed that IMTA setups could effectively decrease nitrogen and phosphorus discharge into coastal waters, thereby aiding in the enhancement of water quality and the preservation of biodiversity.

1.2 Circular Economy Practices

The circular economy framework focuses on reducing waste and optimizing the use of resources, which aligns closely with sustainable practices in aquaculture. In this scenario, circular methods entail reusing water, nutrients, and energy across aquaculture operations. Recent findings indicate that by-products from aquaculture, including fish excrement, can be utilized for generating bioenergy and producing organic fertilizers, thereby lessening dependence on outside resources (Römer *et al.*, 2021).

Additionally, the adoption of closed-loop systems, where waste is continually repurposed, can improve sustainability. Research conducted by Bhatnagar and Devi (2022) revealed that merging aquaculture with agriculture according to circular economy principles can result in enhanced resource efficiency and diminished environmental effects, highlighting the possibilities for cooperative dynamics among various food production methods.

1.3 Sustainable Feed Alternatives

Feed manufacturing plays a crucial role in shaping the ecological footprint of aquaculture. The dependency on fishmeal and fish oil sourced from wild catch generates issues linked to overexploitation and harm to ecosystems. As a result, more research is being directed toward creating sustainable feeding options, such as proteins from plants, meals from insects, and microbial origins (Tacon & Metian, 2013; Naylor *et al.*, 2021).

Recent advancements have investigated alternative protein avenues, including algae and residues from food production, which offer vital nutrients while alleviating the strain on oceanic resources. For instance, research conducted by He *et al*. (2022) revealed that adding insect meal to fish diets not only enhanced growth rates but also lessened the environmental repercussions typically related to conventional feed types.

1.4 Certification and Standards

Certification programs are essential for advancing sustainability in aquaculture by setting benchmarks for ethical practices. Initiatives like the Marine Stewardship Council (MSC) and the Aquaculture Stewardship Council (ASC) offer frameworks for environmentally friendly production techniques, ensuring that products adhere to ecological and social standards (Asche *et al*., 2021).

New studies indicate that consumers are increasingly choosing certified aquaculture goods, reflecting heightened awareness regarding sustainability in food procurement. Research conducted by Seleshe *et al*. (2023) revealed that shoppers are ready to pay extra for seafood that carries sustainability certifications, underscoring the significance of both transparency and traceability within aquaculture supply chains.

Sustainability in aquaculture represents a complex issue that necessitates creative approaches and cooperative strategies. Embracing methods like Integrated Multi-Trophic Aquaculture, concepts of a circular economy, eco-friendly feed options, and established certification criteria can enable the aquaculture sector to progress towards an eco-friendlier future, securing food availability while reducing ecological effects.

2. Technological Innovations

Technological innovations are transforming aquaculture, enhancing productivity, sustainability, and efficiency in fish farming. The integration of advanced technologies in aquaculture practices is crucial for addressing the growing global demand for seafood while minimizing environmental impacts. This section explores key technological advancements, including automation, smart farming, genetic improvements, and bioinformatics.

2.1 Automation and Smart Farming

Automation and intelligent agricultural technologies are transforming aquaculture practices by facilitating the immediate observation and control of water habitats. Implementing tools such as sensors, drones, and Internet of Things devices empowers farmers to gather information regarding water conditions, fish wellness, and feeding behaviors. This reliance on data improves decision-making processes and boosts operational effectiveness.

2.1.1 Sensor Technologies

Sensors are crucial for tracking vital water quality metrics like temperature, pH, levels of dissolved oxygen, and ammonia concentrations. For example, research conducted by Zhang and colleagues in 2021 showed that the implementation of IoT-enabled sensors in aquaculture setups greatly enhanced the management of water quality. This advancement resulted in improved fish growth and lower mortality rates. The ongoing monitoring offered immediate notifications whenever conditions strayed from ideal ranges, making it possible to act promptly.

2.1.2 Drones in Aquaculture

Drones are becoming more prevalent in aquaculture for the purpose of aerial observation and oversight of extensive farming regions. They have the ability to obtain detailed images and gather information regarding fish populations, their feeding habits, and environmental conditions. Research conducted by Hossain *et al*. (2022) emphasized how efficient drones are at evaluating the condition of aquaculture ponds, allowing farmers to detect problems like algal blooms and water quality concerns before they worsen.

2.2 Genetic Improvements

Progress in genetic studies is leading to the creation of aquaculture species that are tougher, quicker to grow, and less susceptible to illnesses.

Techniques in selective breeding along with genomic advancements are utilized to improve favorable characteristics in both fish and shellfish.

2.2.1 Selective Breeding

Selective breeding initiatives have played a crucial role in enhancing the growth speeds and feed efficiency of aquatic species. As an illustration, the creation of genetically enhanced varieties of tilapia has led to notable advancements in their growth rates and resilience against diseases (Gjedrem & Baranski, 2021). Current studies highlight the necessity of preserving genetic variety in breeding efforts to guarantee enduring sustainability and adaptability (Huang *et al*., 2023).

2.2.2 Genomic Technologies

The use of genomic innovations, including CRISPR and genomic sequencing, has created fresh opportunities for enhancing genetics in aquaculture. These methodologies enable accurate alterations of certain genes linked to growth, resilience against diseases, and adaptability to environmental conditions. Research conducted by Liu and colleagues in 2022 revealed the effective use of CRISPR technology to improve disease resistance in common carp, highlighting the promise of focused genetic modifications in aquaculture.

2.3 Bioinformatics and Data Analytics

The combination of bioinformatics with data analysis in aquaculture studies is promoting a greater comprehension of the genetic and environmental elements affecting fish wellness and yield. Through the examination of extensive data collections, investigators are able to recognize trends and relationships that guide breeding strategies and management methods.

2.3.1 Big Data in Aquaculture

The application of large-scale data analysis allows aquaculture farmers to improve their feeding methods, track the development of fish, and forecast market dynamics. For example, research conducted by Zhang and colleagues in 2023 showcased how machine learning techniques can interpret environmental information and estimate fish growth rates, enabling producers to modify their feeding schedules as needed. This approach centered on data not only boosts efficiency but also minimizes feed loss and the effect on the environment.

2.3.2 Health Monitoring Systems

Bioinformatics applications are becoming more prevalent in the creation of health surveillance systems that evaluate both the genetic makeup and physical conditions of fish species. Such systems have the potential to spot initial indicators of disease outbreaks, facilitating preemptive management approaches. A recent investigation by Kim *et al*. (2023) illustrated how bioinformatics can successfully pinpoint genetic markers linked to disease resistance in shrimp, setting the stage for enhanced breeding initiatives.

2.4 Sustainable Feed Technologies

Advancements in feed technology play a crucial role in minimizing the ecological footprint of aquaculture. Conventional fish feeds frequently depend on fishmeal and fish oil, resulting in overfishing and the exhaustion of resources. Recent studies have concentrated on creating sustainable alternatives for feed that are both affordable and kind to the environment.

2.4.1 Alternative Protein Sources

The investigation into different protein alternatives, including insect protein, algae, and leftovers from food manufacturing, is on the rise. Research conducted by He *et al*. (2022) revealed that adding insect protein to fish feed enhanced growth rates while simultaneously decreasing dependency on ocean-derived resources. This movement towards eco-friendly feeding solutions is vital for ensuring the future sustainability of aquaculture.

2.4.2 Precision Feeding Technologies

Precision feeding technologies employ data analysis and automated methods to provide the appropriate feed quantity precisely when needed, reducing waste and boosting feed conversion effectiveness. A study by Li *et al*. (2023)

revealed that precision feeding strategies could notably lower feed expenses and lessen environmental effects, all while promoting faster fish growth.

Technological advancements are transforming the aquaculture sector, presenting strategies to improve productivity, sustainability, and operational efficiency. By adopting automation, genetic advancements, bioinformatics, and sustainable feed developments, the aquaculture field can satisfy the rising demand for seafood while reducing its ecological impact.

3. Health Management and Disease Control

Health oversight and illness control are vital elements of sustainable fish farming methods. The aquaculture sector confronts considerable obstacles from illnesses that may result in major financial setbacks and jeopardize food safety. Robust health management approaches are crucial for preserving fish well-being, enhancing production effectiveness, and guaranteeing the viability of aquaculture frameworks. This segment examines important features of health oversight, such as vaccination techniques, probiotics, protective measures, and the influence of genomics on resilience to diseases.

3.1 Vaccination and Disease Resistance

Immunization stands out as a highly efficient approach to managing illnesses in fish farming. The creation and use of vaccines can greatly lower death rates and enhance the general well-being of fish communities.

3.1.1 Vaccine Development

Recent progress in the creation of vaccines has centered on devising potent solutions against prevalent aquatic microorganisms, including bacteria, viruses, and parasites. For instance, research conducted by Baker *et al.* (2020) underscored the effective formulation of both inactivated and live attenuated vaccines targeting viral illnesses in fish, like infectious pancreatic necrosis (IPN) and viral hemorrhagic septicemia (VHS). These vaccines have demonstrated encouraging outcomes in safeguarding fish communities from epidemics.

3.1.2 Immune Response Enhancement

Investigations have additionally concentrated on improving the immune defense of fish via vaccination methods. A research effort by Klesius and colleagues in 2021 revealed that incorporating adjuvants into vaccine designs could greatly enhance the immune reaction in tilapia, resulting in better defense against illnesses. Grasping the immune processes in fish is essential for creating vaccines and vaccination strategies that are more efficient.

3.2 Probiotics and Microbiome Research

Probiotics consist of living microbes that provide health advantages to the host when given in sufficient quantities. In the field of aquaculture, there is a growing application of probiotics to improve the health of fish and boost their growth efficiency.

3.2.1 Role of Probiotics

Probiotics have the potential to enhance digestive wellness, increase the uptake of nutrients, and strengthen the immune response in fish. A comprehensive review conducted by Merrifield and Carnevali in 2014 revealed that adding probiotics to fish feed resulted in better growth performance and lower death rates from illnesses. Additionally, probiotics can prevent the proliferation of harmful bacteria, thereby diminishing the likelihood of infections.

3.2.2 Microbiome Studies

Recent studies have concentrated on grasping the fish microbiome and its significance in health management. The intestinal microbiome is essential for processes like digestion, immunity, and resistance to diseases. Research conducted by Nayak in 2010 highlighted the necessity of upholding a robust gut microbiome to ensure ideal fish wellness. Methods like metagenomics are currently employed to investigate the variety and roles of microbial populations in fish, offering valuable information on how to adjust these populations for improved health results.

3.3 Biosecurity Measures

Establishing biosecurity practices is crucial for averting the emergence and transmission of illnesses within aquaculture environments. These biosecurity strategies assist in reducing dangers associated with harmful organisms and safeguarding the well-being of fish communities.

3.3.1 Risk Assessment

Carrying out comprehensive evaluations of risks is the initial stage in creating efficient biosecurity strategies. It is essential to recognize possible origins of pathogens, including polluted water, tools, and individuals, to apply focused control strategies (Bregnballe, 2015).

3.3.2 Biosecurity Practices

Typical biosecurity measures consist of isolating affected individuals, ongoing health assessments, and cleanliness routines. Research conducted by Hine and colleagues in 2022 highlighted the necessity of enforcing rigorous biosecurity protocols in hatcheries and agricultural settings to avert disease incidents. This entails restricting entry to facilities, sanitizing gear, and frequently assessing the health of fish to identify any indications of illness promptly.

3.4 Genomics and Disease Resistance

Progress in genomics is creating fresh opportunities for comprehending disease resistance in aquatic farmed species. The ability to select genetically for disease resistance is growing more practical, allowing for the establishment of more robust fish populations.

3.4.1 Genomic Selection

Genomic selection refers to the application of molecular markers for pinpointing fish that exhibit sought-after characteristics, like resistance to diseases. Research conducted by Gjedrem *et al*. in 2021 emphasized the promising role of genomic selection in boosting viral disease resistance among salmonids. By choosing individuals with advantageous genetic traits, breeders have the ability to improve the general health and robustness of fish populations.

3.4.2 Understanding Genetic Mechanisms

Investigating the genetic factors that contribute to disease resistance is essential. A research project conducted by Wang and colleagues in 2023 examined the genetic underpinnings of tilapia's resistance to bacterial infections, pinpointing significant genes linked to immune reactions. Gaining insight into these processes can guide breeding initiatives focused on improving disease resistance among aquaculture species.

Managing health and controlling diseases are critical for the ongoing viability and effectiveness of aquaculture systems. By adopting successful vaccination methods, employing probiotics, applying biosecurity protocols, and utilizing genomic innovations, the aquaculture sector can boost fish well-being, minimize disease occurrences, and elevate overall productivity levels.

4. Socioeconomic Aspects

The socioeconomic factors associated with aquaculture are vital in influencing the industry's ability to sustain and advance. As the sector of aquaculture expands, it becomes imperative to grasp its effects on nearby communities, economic systems, and food availability. This portion examines important socioeconomic elements, such as involvement of communities, job possibilities, market behavior, and aquaculture's contribution to ensuring food security.

4.1 Community Engagement and Empowerment

Aquaculture can greatly impact nearby communities, especially in countryside regions where fishing and agriculture are key means of making a living. Involving local populations in aquaculture activities promotes empowerment and strengthens social bonds.

4.1.1 Community-Based Aquaculture

Community-focused aquaculture projects engage local participants in the design, oversight, and implementation of aquaculture endeavors. Such projects can strengthen local engagement and guarantee that advantages are fairly shared. Research conducted by Béné and colleagues in 2016 emphasized the effectiveness of community-based aquaculture in advancing sustainable methods and enhancing living standards across diverse areas, such as Southeast Asia and Africa. By including local populations, community-based aquaculture cultivates a feeling of accountability and care for aquatic resources.

4.1.2 Gender Inclusion

Gender equality in aquaculture is crucial for harnessing the full potential of the industry. Women often contribute significantly in aquaculture, but their input is commonly disregarded. A study by Béné et al. (2021) highlights the need for supporting women in aquaculture by providing education and access to necessary resources. By fostering gender balance, aquaculture can strengthen community resilience and elevate broader socioeconomic results.

4.2 Employment Opportunities

Aquaculture is a sector that requires a significant amount of manual work and offers a wide range of job possibilities in several areas, such as fish cultivation, processing, and distribution. Expanding aquaculture has the potential to help reduce poverty and promote economic progress.

4.2.1 Job Creation

The growth of aquaculture generates employment opportunities not just in farming, but also in related industries like feed manufacturing, equipment production, and logistics. As stated by the Food and Agriculture Organization (FAO, 2022), aquaculture plays a crucial role in sustaining the livelihoods of millions around the world, especially in less developed nations. Research conducted by Rönnbäck *et al.* (2020) revealed that aquaculture has the potential to create substantial job prospects for disadvantaged populations, which can lead to a decrease in poverty and an enhancement in quality of life.

4.2.2 Skill Development

As the fish farming industry develops, the demand for qualified personnel is increasing. Instructional initiatives that emphasize optimal methods, eco-friendliness, and the use of new technologies are vital for providing workers with essential competencies. A study conducted by Hishamunda and colleagues in 2020 reveals that pouring resources into training and education can boost efficiency and promote the enduring success of aquaculture businesses.

4.3 Market Dynamics and Consumer Preferences

The aquaculture industry is shaped by multiple elements, such as what consumers want, cost considerations, and rivalry with natural fishing operations. Grasping the intricacies of the market is essential for ensuring the long-term viability of aquaculture.

4.3.1 Consumer Awareness

Consumers are growing more conscious of sustainability concerns connected to seafood farming. Findings from Kumar *et al*. (2022) reveal that buyers are open to spending more for sustainably harvested aquaculture goods. This change in consumer tendencies is propelling the implementation of eco-friendly methods in aquaculture, as producers strive to satisfy market needs.

4.3.2 Market Access

Access to markets plays a vital role in the prosperity of aquaculture businesses. Small farmers frequently encounter difficulties in reaching markets because of insufficient infrastructure and scarce resources. Research conducted by Dey *et al*. (2021) emphasizes the need for forming cooperatives and creating market connections to boost the competitiveness of smaller aquaculture producers. By enhancing market access, small-scale farmers have the potential to boost their earnings and positively impact local economies.

4.4 Aquaculture and Food Security

Aquaculture is crucial for improving food security, especially in areas where conventional fishing is on the decrease. This industry has the potential to offer a consistent supply of protein and vital nutrients for increasing populations.

4.4.1 Nutritional Contributions

Aquaculture plays a crucial role in the world's food resources, delivering a major share of the seafood consumed globally. As reported by the FAO in 2022, more than half of the world's fish output stemmed from aquaculture in recent times. Fish serves as a vital provider of protein, vitamins, and minerals, making it a key aspect of a nutritious diet, particularly in nations that are still developing.

4.4.2 Resilience to Climate Change

As traditional fisheries face challenges due to climate change, aquaculture presents a more robust option for food production. According to the findings of Barange *et al*. (2018), aquaculture can alleviate the impacts of climate change on food security by ensuring a reliable supply of seafood. Implementing sustainable aquaculture methods can improve adaptability to environmental shifts and provide a steady food source.

The social and economic factors surrounding aquaculture are crucial for its ongoing sustainability and growth. By promoting community involvement, generating job opportunities, analyzing market trends, and improving food security, the aquaculture industry can enhance the welfare of local populations and contribute to the global economy. Tackling these social and economic issues is vital for maintaining the long-term success of aquaculture as an essential food resource and means of livelihood.

Conclusion

The horizon of aquaculture investigation is set to experience notable progress fueled by new trends and creative methodologies. With the increasing worldwide appetite for seafood, the sector encounters difficulties concerning sustainability, ecological effects, and food availability. Tackling these issues necessitates a comprehensive strategy that includes technological advancements, eco-friendly practices, and improved management approaches.

Important movements in aquaculture inquiry involve the implementation of precision agriculture methods, utilizing data analysis and automation to enhance efficiency in production and resource utilization. The incorporation of biotechnological advancements, such as enhancements in genetics and resistance to diseases, offers potential for creating strong aquaculture species that can adapt well to fluctuating environmental circumstances.

Furthermore, an increasing focus on sustainability is influencing the paths taken in research, highlighting the need for alternative feed options, closed-loop systems, and minimizing the environmental impact of aquaculture. Advancements in biosecurity and health management will also play a vital role in reducing disease threats and promoting the well-being of aquatic organisms.

As aquaculture progresses, cooperation across various disciplines among researchers, industry participants, and policymakers will be crucial for driving innovation and applying research discoveries in real-world contexts. By concentrating on sustainability, technological advancements, and community involvement, the future of aquaculture research can enhance a robust and effective industry that fulfills the demands of an expanding global population while safeguarding aquatic environments.

In summary, the upcoming paths in aquaculture research are poised to revolutionize the sector, enhancing its sustainability, efficiency, and adaptability in addressing the difficulties of the 21st century. Adopting these trends and advancements will be essential for ensuring the enduring success of aquaculture as a significant contributor to worldwide food supply.

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CHAPTER V

GENE EXPRESSION BIOMARKERS IN AQUACULTURE PRODUCTION: TOWARDS SUSTAINABLE BREEDING PRACTICES

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Introduction

Aquaculture is the fastest-growing sector of food production, crucial for meeting global protein demand (FAO, 2020, Yue et al., 2022). A cornerstone of aquaculture success is effective reproductive biology – high-quality eggs and sperm from robust broodstock drive reliable fry production and stock renewal (Bhat et al., 2025). However, reproduction in aquatic animals can be complex and easily disrupted by suboptimal conditions. Understanding the molecular underpinnings of reproduction is therefore vital for sustainable aquaculture. In particular, gene expression plays a central role in regulating reproductive processes (Qiao et al., 2024, Bhat et al., 2025).

Biomarkers – measurable biological indicators – have emerged as powerful tools in this context. A biomarker can be a specific mRNA, protein, or epigenetic mark that signifies a physiological state or capacity. In reproduction, biomarkers are used to gauge sexual maturation, gamete quality, or stress responses affecting fertility. For example, certain genes in lipid metabolism were identified as potential biomarkers correlating with shrimp broodstock fecundity (Ahmad et al., 2023). By tracking such molecular indicators, farmers and researchers can early-detect reproductive readiness or problems, enabling proactive management. Overall, integrating gene expression biomarkers into aquaculture promises more sustainable production through optimized breeding cycles, better selection of breeders, and mitigation of reproductive failures.

Relationship Between Gene Expression and Reproduction

Gene expression tightly orchestrates reproduction in aquatic animals through conserved mechanisms (Siauciunaite et al., 2019). In fish, the hypothalamic–pituitary–gonadal (HPG) axis exemplifies this control: environmental cues (like day length) trigger hypothalamic genes for gonadotropin-releasing hormone (GnRH), which in turn regulate pituitary gonadotropins (e.g. FSH and LH genes) that activate gonadal genes for steroidogenesis and gametogenesis (Bhat et al., 2025). This cascade ensures that gamete development (oogenesis and spermatogenesis) proceeds in sync with favorable conditions. Common genetic pathways are seen across species – for instance, genes for steroid hormone synthesis and germ cell development are fundamental to reproduction in most fish and invertebrates. Fishes have a well-characterized HPG axis and sex differentiation system, and identifying gene expression patterns in brain and gonads has been key to analyzing their sexual development (Qiao et al., 2024).

Despite reproductive patterns ranging from spawning fish to brooding shrimps, many molecular players have been evolutionarily conserved. Vasa, for example, is a highly conserved germ cell marker gene present in animals from mollusks to fish, and its expression denotes the presence and proliferation of gametes (Nagasawa et al., 2013; Çek et al., 2016). Likewise, genes in the steroidogenic cytochrome P450 family (such as aromatase or 11β-hydroxylases) mediate estrogen and androgen production in vertebrates, while in crustaceans analogous pathways (ecdysteroids, methyl farnesoate) involve related enzyme genes (Lafont & Mathieu, 2007). These shared pathways mean that core aspects of reproductive gene regulation – from germ cell formation to hormone signaling – recur across aquatic taxa. Understanding these general mechanisms provides a baseline for exploring species-specific reproductive genetics (Qiao et al., 2024). In essence, reproduction is a gene-driven process, and disruptions in gene expression due to stress, pollution, or genetic mutation can lead to failed spawning or poor gamete quality. By studying gene expression profiles during key reproductive stages, researchers can decipher critical control points and develop biomarkers that apply broadly across species.

Species-Specific Examples of Gene Expression

Different aquaculture species offer case studies of how particular genes influence reproduction:

- **Shrimp (Penaeus monodon)** Lipid metabolism in shrimp is important for successful reproduction because the ovaries need significant lipid reserves for egg development. A study on giant tiger prawn identified several genes in lipid metabolic pathways whose expression correlated with broodstock performance. Notably, a fatty acid elongase (PmElovl4), a cyclooxygenase (PmCOX), and a SUMO conjugation enzyme were upregulated in high-performing female shrimp (Rotllant et al, 2015) In contrast, some genes showed reduced ovarian expression in domesticated lines, pointing to breeding-related changes. Moreover, the expression of a fatty acid binding protein (PmFABP) in the hepatopancreas was positively correlated with the shrimp's gonadosomatic index, and a cytochrome P450 gene (PmCYP4, involved in lipid oxidation) correlated with ovarian total lipid content ((PDF) Identification of genes involved in reproduction and lipid pathway metabolism in wild and domesticated shrimps). These patterns suggest that shrimp with robust ovarian development exhibit distinct upregulation of lipid-processing genes. Such genes can serve as biomarkers of maturation: indeed, enzymes of lipid synthesis and steroid biosynthesis were proposed as indicators of reproductive readiness in P. monodon ((PDF) Identification of genes involved in reproduction and lipid pathway metabolism in wild and domesticated shrimps). This example highlights that adequate lipid metabolism (at the gene level) is critical for crustacean fertility, aligning with the practical need for high-quality diets to induce shrimp breeding.

- **European Seabass (Dicentrarchus labrax)** – As a cultured marine fish, European seabass provides an example of gene markers for male reproduction. During spermatogenesis, the expression of certain genes is essential for testis development. Vasa (also called DDX4) is expressed in spermatogonia and spermatocytes, marking the presence of germ cells required for continuous sperm production. It is often used as a biomarker for the germ cell population in male fish. In addition, seabass (like many teleosts) possesses two androgen receptor genes (ARα and ARβ) which mediate the effects of androgens (like 11-ketotestosterone) on sperm maturation. The ARβ subtype is highly expressed in testes and its transcription levels rise as germ cells differentiate, indicating active androgen signaling. Another key gene is CYP11B1, coding for 11β-hydroxylase, the enzyme that produces 11-ketotestosterone – the principal male sex steroid in many fish. In seabass, CYP11B1 expression in Leydig cells of the testis supports androgen synthesis necessary for spermatogenesis. Studies have shown that elevated transcripts of vasa, CYP11B1, and ARβ coincide with peak spermatogenic activity (ripe testes), whereas aberrant expression of these can signal reproductive dysfunction (e.g. low sperm count). While each of these genes has a distinct role, together they exemplify how a suite of gene expression markers can diagnose or predict male fertility status. For instance, a drop in ARβ or steroidogenic enzyme mRNAs might warn of endocrine issues affecting sperm production. Thus, monitoring such spermatogenesis-related genes in species like seabass can inform broodstock selection (choosing males with active spermatogenesis) and management of factors (like temperature or photoperiod) that influence their expression.
- **Rainbow Trout (Oncorhynchus mykiss)** – In female fish, estrogen signaling and yolk formation are crucial processes governed by gene expression. In trout, the ovarian follicle produces estrogen (17β-estradiol) that binds estrogen receptors (ERα/β) in the liver,

activating the gene for vitellogenin (Cotter et al., 2013; Nagata et al., 2021). Vitellogenin (vtg) is an egg yolk precursor protein, and its mRNA is massively upregulated in the liver of maturing females, resulting in high vitellogenin protein in the bloodstream. Vitellogenin is a classic biomarker: its presence in blood indicates that a female is responding to estrogen and developing eggs. In healthy trout, one expects rising vitellogenin levels as ovaries mature. Conversely, suppressed vitellogenin gene expression can impair oocyte growth. One study showed that exposure to a heavy metal (zinc) reduced blood vitellogenin levels and led to poor egg development in female fish (Bhat et al., 2025). The same treatment also lowered 11-ketotestosterone in males, halting spermatogenesis (Bhat et al., 2025), underscoring that disrupting these key genes/hormones devastates reproduction. In normal conditions, robust vitellogenin expression corresponds with good fecundity. Additionally, the estrogen receptor genes themselves (especially ERα in liver and ovary) are critical – if ER expression is low, the vitellogenic response will be weak. Thus, measuring ER and vtg transcripts provides insight into a trout's reproductive endocrine status. Aquaculture programs often use such biomarkers to evaluate if females have been adequately primed (for example, by photoperiod manipulation) – an increase in vitellogenin mRNA or protein confirms that the fish are entering vitellogenesis and ready for spawning. This example illustrates the tight link between gene expression and female reproductive output, and how gene-based biomarkers (ER, vtg) can indicate spawning readiness or the impact of environmental disruptors on reproduction (Bhat et al., 2025).

- **Mussels (Mytilus spp.)** – Bivalve mollusks like mussels lack easily observable sex traits, making molecular markers particularly valuable for studying their reproduction. Recent transcriptomic research on the mussel Mytilus coruscus uncovered an interesting interaction between a gene and a regulatory RNA in gonadal development

(Frontiers | Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus). The gene DMRT4 (a member of the Doublesex-Mab3 related transcription factor family) was identified as a likely sex differentiation factor in mussels. At the same time, a microRNA called miR-317 was found to be differentially expressed between testes and ovaries (Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus – DOAJ) (Frontiers | Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus). Bioinformatic target analysis predicted that miR-317 would bind to the 3'UTR of DMRT4 mRNA, and experimental validation using a luciferase reporter assay confirmed that miR-317 can directly regulate DMRT4 (Frontiers | Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus) (Frontiers | Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus). In practical terms, miR-317 appears to suppress DMRT4 expression. The study noted that miR-317 levels were higher in testes than ovaries, correlating with lower DMRT4 in testes (Frontiers | Transcriptome sequencing analysis of sex-related genes and miRNAs in the gonads of Mytilus coruscus). This suggests miR-317 might help down-regulate DMRT4 in males, whereas in females DMRT4 stays elevated (due to less miR-317), potentially influencing ovary development. The interaction of DMRT genes and microRNAs is a novel layer of gene expression control in molluscan reproduction. For aquaculture of mussels, such findings are valuable because they point to molecular biomarkers for sex and maturation in otherwise monomorphic animals. Measuring miR-317 or DMRT4 transcripts could allow farmers to determine sex ratios in mussel populations or to monitor gonadal maturation (e.g., a drop in miR-317 and rise in DMRT4 might signal an individual maturing as female). This example demonstrates the complexity of gene regulation (mRNA–miRNA interactions) in aquatic reproduction and expands the toolkit of biomarkers beyond protein-coding genes to include non-coding RNAs.

- **Tilapia (Oreochromis spp.)** – Tilapia are known for environmental sex determination: genetic males or females can be reversed by temperature or hormone treatments (Baroiller et al, 2009). Epigenetic regulation has a prominent role in this sexual plasticity. Key sex-related genes in tilapia, such as DMRT1 (a testis-determining gene) and steroidogenic enzymes like CYP11B2 (11β-hydroxylase, involved in androgen and corticosteroid synthesis), have been shown to undergo epigenetic modifications during sex differentiation. For instance, high-temperature rearing (which skews tilapia to maleness) is associated with changes in DNA methylation at the aromatase gene and possibly at DMRT1, leading to altered expression. In general, tilapia that develop as males tend to have higher DMRT1 expression in the gonad and potentially higher CYP11B2 expression (since certain androgens or cortisol may be elevated), and differences in DNA methylation patterns have been observed between sexes (Jiang et al., 2016, Liu, 2022). Epigenetic markers can thus indicate the developmental trajectory: e.g., hypermethylation of the ovarian aromatase gene or hypomethylation of DMRT1 might predict a phenotypic male. Moreover, experiments have found that treatments like temperature stress can induce long-lasting changes in methylation that affect reproductive gene expression into adulthood. From an aquaculture perspective, these epigenetic insights are valuable for broodstock management. They suggest that the early rearing environment can leave epigenetic "biomarkers" on the genome that forecast reproductive parameters (such as sex ratio or maturation timing). Monitoring genes like CYP11B2 and DMRT1 at both expression and epigenetic levels could help identify fish that have been masculinized by temperature or to confirm the success of all-female YY breeding programs. This illustrates how epigenetic regulations intersect with classical gene expression to control tilapia reproduction and how biomarkers in this case might include not just RNA/protein levels but DNA methylation status of critical genes (Anastasiadi & Beemelmanns, 2023, Whelan et al., 2023).

4. Identification and Classification of Biomarkers

Biomarkers in reproductive biology can be classified by their molecular nature. The main categories are mRNA-based, protein-based, and epigenetic biomarkers:

- **mRNA-based biomarkers:** These are specific mRNA transcripts whose abundance reflects a reproductive state. They are identified typically via transcriptomics or targeted PCR. For example, the vitellogenin mRNA in a female fish's liver is a biomarker of estrogen stimulation and ovarian maturation – high vitellogenin transcript levels indicate active yolk production (Bhat et al., 2023). Likewise, spermatogenesis-related mRNAs (such as vasa or dmrt1) in testes can serve as indices of spermatogenic activity. mRNA biomarkers are appealing because of their sensitivity: transcript levels can change rapidly in response to stimuli, providing an early readout. High-throughput sequencing (RNA-Seq) has greatly expanded the discovery of such biomarkers. By comparing gonadal transcriptomes under different conditions, researchers have mined countless candidate genes tied to sex differentiation and maturation (Qiao et al., 2024). For instance, in mussels, thousands of differentially expressed genes between ovary and testis were identified, but only a subset (like dmrt4) with large expression differences become practical biomarkers (Wang et al., 2022). To qualify as a useful biomarker, an mRNA should show a consistent, diagnostic pattern correlated with a trait of interest such as maturity, sex, or fertility. mRNA biomarkers are usually detected by quantitative PCR in practice, which allows hatchery managers to, say, screen broodstock via minimally invasive biopsies. If a female's ovarian tissue shows low vtg "vitellogenin" mRNA, it might signal an issue preventing normal oogenesis. In summary, mRNA biomarkers are versatile indicators of reproductive physiology – essentially a molecular snapshot of gene activity linked to fertility (Arukwe & Goksøyr, 2003).

- **Protein-based biomarkers:** These include hormones, enzymes, or other proteins measurable in tissues or bodily fluids that signify reproductive status. Because proteins are the effectors of biology, protein biomarkers are often directly tied to functional outcomes. A prime example is vitellogenin protein level in blood plasma, widely used to assess female fish maturation or exposure to estrogenic substances (Bhat et al, 2025). Another is 17α,20β-dihydroxyprogesterone (17,20β-P) hormone, which in many fish spikes during final oocyte maturation and can be measured as a spawning indicator (Berlinsky and Specker, 1991, Thrupp et al., 2018). In males, plasma 11-ketotestosterone is a biomarker correlating with sperm development; low 11-KT often accompanies poor spermatogenesis (Bhat et al., 2025, Schultz, 2005). Enzymes present in reproductive tissues, like alkaline phosphatase in fish milt or lectins in eggs, can also serve as quality markers. Protein biomarkers are often detected via immunoassays (ELISA, RIA) or activity assays (Don et al., 2005). They have the advantage of sometimes being detectable non-lethally (for instance, measuring hormone levels from a blood sample). The downside is that protein changes might lag behind mRNA changes due to translation and stability factors. Nonetheless, protein indicators are essential – aquaculture operations routinely monitor hormone profiles to time spawning induction or verify sex reversal treatments. In crustacean aquaculture, for example, the vitellin/vitellogenin protein content in the hemolymph or ovary is measured to judge the stage of ovarian maturation (Boucard et al., 2002). Overall, protein biomarkers provide a direct window into the physiological state: if a supposedly gravid fish has low vitellogenin protein, it's a clear sign of reproductive impairment (Hara et al., 2016). Combining mRNA and protein biomarker data often gives the most robust assessment (McDermott et al., 2013).

- **Epigenetic biomarkers:** These are modifications on DNA or chromatin that affect gene expression without altering the genetic code. In aquaculture reproduction, DNA methylation patterns and histone modifications are emerging as epigenetic biomarkers. For instance, the methylation status of the aromatase gene promoter in sex-changing fish can predict gender outcome – high methylation (silencing) is linked with maleness, while low methylation keeps the gene active for femaleness (Hosseini et al, 2022, Wu et al, 2016). Epigenetic marks can be stable recorders of past environmental influences. A fish exposed to high-temperature stress during development might carry a persistent methylation signature at key genes (like dmrt1 or cyp19a1) that influences its reproductive physiology (Matsuda et al., 2023). Such patterns can be detected via bisulfite sequencing or methylation-specific PCR. As a biomarker, global DNA methylation in gonads has been correlated with gametogenic stage and sex differentiation (Liu, 2022). One study in common carp found thousands of regions with differential chromatin accessibility between testes and ovaries, indicating a broad epigenetic reprogramming underlying sex differences (Yu et al., 2024). Epigenetic biomarkers are particularly relevant for traits like puberty onset or sex ratios which can be affected by early rearing conditions. They could also help in broodstock selection—e.g., breeders with "epigenetically healthy" sperm (low DNA fragmentation and normal methylation patterns) might yield better offspring. Although the application of epigenetic biomarkers in routine aquaculture is still in its infancy, research suggests great potential. Epigenetic changes have been tied to fish reproduction and development in many studies (Liu, 2022), so it is conceivable that in the future, a quick methylation assay of a gene panel could inform on broodstock fertility or the long-term effects of a hatchery practice.

Epigenetic marks are less transient than mRNAs or proteins, giving a sort of memory – a unique angle for biomarker development (Day & Sweatt, 2011).

In practice, these biomarker types are complementary. For example, one could monitor an mRNA (fast response) and a protein (physiological effector) together to get a fuller picture. Notably, the special issue on aquatic animal reproduction highlights the need to study genes and epigenetic modifications as markers of sex differentiation and maturation (Qiao et al, 2024). By classifying biomarkers into these categories, researchers can design multi-level monitoring systems for aquaculture: transcriptomic assays for early detection, proteomic assays for functional validation, and epigenetic screens for heritable or long-term effects.

Cryopreservation and Its Effects on Gene Expression

Cryopreservation of gametes (sperm, eggs, or embryos) is a valuable technique for aquaculture breeding programs and gene banking. However, the process of freezing and thawing imposes genetic and cellular stress on these cells. Genetic stress caused by cryopreservation can include DNA damage (strand breaks, base oxidation) and altered gene function. For instance, freezing semen in liquid nitrogen can lead to oxidative stress that fragments DNA and disrupts mRNA integrity. Such damage may not outright kill the gametes but can have sub-lethal effects that manifest during fertilization or embryonic development. As a result, scientists monitor gene expression changes as a means to gauge cryopreservation impact. After thawing, gametes or resultant embryos often show differential expression of stress-response genes. Heat shock proteins (like hsp70), antioxidant enzymes, and DNA repair genes can be upregulated as the cell attempts to mitigate cryo-injuries (Riesco & Robles, 2013).

One striking observation is that cryopreservation can perturb the expression of growth and development genes in the ensuing embryos. In a study on fish embryo development, researchers compared gene expression between embryos fertilized with fresh vs. cryopreserved sperm. They found that several genes in the growth hormone/insulin-like growth factor axis were overexpressed after hatching in the cryopreservation group. Specifically, transcripts of IGF1, IGF1 receptors (Igfr1a, Igfr1b), and growth hormone (GH1, GH2) were higher in larvae originating from frozen sperm (Labbê et al, 2013). One interpretation is that the embryos experienced a compensatory response – perhaps the mild stress of cryopreservation triggered an endocrine boost to support development. Alternatively, it could signal developmental dysregulation. In either case, tracking these gene changes is informative. It shows that even if cryopreserved gametes produce viable offspring, the molecular profile of those offspring may shift, which could have implications for growth or health.

Beyond global effects, some specific genes that influence cryotolerance—the ability of cells to withstand freezing has been pinpointed by researchers. Two such candidates are IGF1 and SOX17. IGF1 (insulin-like growth factor 1) is known for its cell survival and growth-promoting properties, and it appears highly expressed in early germ cells (spermatogonia) of fish (Viñas & Piferrer, 2008). Higher baseline levels of IGF1 might protect cells from apoptosis during freezing and thawing, making it a potential biomarker of cryotolerance. Similarly, SOX17, a transcription factor expressed in early embryonic cells and germline progenitors (Viñas & Piferrer, 2008), could be crucial for maintaining cell integrity under stress. If spermatogonial cells or embryos with robust SOX17 expression survive cryopreservation better, then SOX17 expression could be used as a marker to select for cryo-resilient lines. In practical breeding terms, this could mean screening broodstock for those whose sperm have high IGF1 mRNA – these might yield higher post-thaw fertility.

On the other hand, lack of induction of protective genes may explain why some gametes suffer lethal damage from cryopreservation. By monitoring gene expression, hatchery managers can evaluate the quality of cryopreserved gametes: for example, measuring expression of pro-apoptotic genes versus anti-apoptotic ones post-thaw can indicate if the cryoprotocol is too harsh. Adjustments in cryoprotectant, cooling rate, or thawing method could then be made to improve outcomes.

In summary, cryopreservation is a double-edged sword – it ensures genetic resources are conserved, but it can induce subtle changes in gene expression that need to be understood. Continuous monitoring of key genes (like IGFs, stress proteins, and developmental regulators) in cryopreserved vs. fresh gametes provides insight into the cellular state of frozen-thawed material. This not only helps in refining cryopreservation techniques (aiming for minimal perturbation) but also in identifying biomarker genes that predict which gametes are best suited for freezing. Ultimately, combining classical cryobiology assessments (motility, viability) with molecular assessments (gene expression profiling) yields a much fuller picture of gamete quality for aquaculture purposes.

Contributions of Biomarkers to Reproductive Efficiency

The use of biomarkers has tangible benefits for improving reproductive efficiency in aquaculture. They contribute in several ways:

- **Early detection and selection:** Biomarkers allow early identification of sex, maturity, or reproductive potential, which is invaluable for broodstock selection. For instance, genetic sex markers (like the presence of a Y-chromosome-specific gene or sex-biased gene expression) can be used to sex juvenile fish that are not yet visually dimorphic. This enables the implementation of monosex culture (all-male or all-female stocks) which in many species yields better growth and production (Qiao et al., 2024). Tilapia farmers, for example, prefer all-male stocks (males grow faster), and DNA or RNA markers for genetic sex help produce these via breeding or sorting, without hormonal treatments. Early maturity markers are another example: a spike in vitellogenin or FSH-beta gene expression in a young age could indicate precocious maturation, which is undesirable in grow-out. Those individuals might be selectively culled or separated. In shrimp, detecting vitellogenin expression in female hepatopancreas can tell if a broodstock is maturing; those with strong signals can be selected for spawning, improving efficiency. Spermatogenesis biomarkers (like testicular dmrt1 or AR levels) can similarly identify males with active sperm production. By using such molecular cues, hatcheries can select only the broodstock that are truly ready to spawn, avoiding wasted effort on unripe individuals. This precision speeds up breeding cycles and increases the yield of viable embryos. Moreover, early detection of reproductive issues is possible – if a biomarker like vitellogenin is expected to rise but doesn't, it flags a problem with the female (perhaps nutritional or hormonal) that can be addressed before a spawn fails.

- **Impact on genetic improvement programs:** Biomarkers integrate with selective breeding and genetic improvement by serving as selection criteria or proxies for complex traits. Traditional breeding for reproductive traits (e.g. higher fecundity, better hatch rates) is slow because those traits may only manifest at sexual maturity and are influenced by environment. However, if one can identify a biomarker that reliably correlates with the desired trait, it can be used in Marker-Assisted Selection (MAS). For example, if a particular allele or expression pattern of a gene is associated with higher egg output, breeders can screen for it in juveniles. This marker-assisted breeding accelerates gains by selecting at the DNA or RNA level rather than waiting for phenotypes. Indeed, the advent of high-density genomic markers and sequencing has made it feasible to map quantitative trait loci (QTLs) for reproduction and use them in breeding (Peng et al., 2016; Yue et al., 2022). Programs in species like oysters and salmon are beginning to incorporate genomic selection where genomic predictors (including SNP markers in reproductive genes) help rank broodstock for breeding value. Another example is improving stress resilience of reproduction: if fish that maintain normal hsp70 expression under thermal stress have better spawning, that expression stability could be a selection target (Yamashita et al., 2010). By saving time and cost in breeding, biomarkers greatly enhance efficiency – MAS can achieve in a few generations what traditional selection would in many (Yu et al., 2022). Additionally, biomarkers help in evaluating the success of genetic improvements. Suppose a line is bred for high fecundity; one can verify if expected molecular changes (like higher gonadotropin levels or larger ovary size gene expression signatures) are indeed present, confirming that the selection is having the intended effect at a biological level. This feedback loop guides breeders to refine their criteria continuously.

- **Monitoring reproductive quality:** Biomarkers provide ongoing monitoring of broodstock and gamete quality, which is key to consistent fry production. Even after selecting good broodstock, their condition can vary with handling, age, or environment. By regularly checking biomarkers, hatchery managers can ensure quality control. For instance, a decline in sperm motility could be investigated by looking at apoptotic gene expression or membrane integrity markers in sperm – if genes indicating DNA fragmentation or oxidative stress are elevated, it suggests the male's sperm quality is deteriorating (perhaps due to age or stress) (Sakkas & Alvarez, 2010). The manager might then retire that male from the breeding program. In females, egg quality is a big determinant of larval survival. Certain maternal mRNAs in eggs (such as zar1 or bcl-2) are linked to embryo viability; if these are abnormally low, it can predict poor outcomes (Aegerter et al., 2005). Measuring such mRNA biomarkers in a batch of eggs could inform whether to proceed with incubation or not. Additionally, hormone profiles (like consistently low 17β-estradiol in a female that should be gravid) alert staff to issues like atresia or disease. Biomarkers also aid in health monitoring – e.g. subclinical infections or stress can be caught by checking immune gene expression in gonads, which often correlates with reduced reproductive performance. By integrating biomarker monitoring (perhaps via routine blood tests or biopsy gene expression assays) into broodstock management, facilities can maintain high reproductive efficiency: problems are caught and corrected early, and only high-quality gametes are used for propagation. This reduces wasted spawnings and improves larval yield. In short, biomarkers act as a continual feedback mechanism, guiding hatchery decisions in real time to sustain optimal reproductive output.

In all these ways, biomarkers significantly contribute to more efficient and reliable breeding in aquaculture. They enable a shift from reactive to proactive management – rather than discovering a fertility problem after a spawn fails, biomarkers allow anticipation and intervention. As aquaculture moves toward more technology-driven approaches, biomarker-based selection and monitoring will likely become standard practice, much like water quality testing is today, thereby boosting both productivity and sustainability of aquaculture operations.

Future Perspectives and Recommendations

The integration of cutting-edge technologies is poised to enhance the use of biomarkers in aquaculture reproduction even further. Several promising directions are emerging:

- **Next-Generation Sequencing (NGS) technologies:** The rapid evolution of sequencing (and other "omics" tools) will continue to expand our knowledge of reproductive gene networks. Transcriptome sequencing (RNA-Seq) has already enabled the discovery of numerous candidate genes tied to sex differentiation, gonad development, and gamete quality (Qiao et al, 2024). As sequencing becomes cheaper and faster, it could be applied routinely – for example, performing an RNA-Seq snapshot of broodstock gonads each season to identify any anomalies in gene expression. This could uncover subtle issues (like declines in expression of a fertility gene) before they affect spawning. Moreover, single-cell RNA sequencing might be applied to gonads to map expression changes in individual cell types (germ cells, Sertoli cells, follicle cells) during maturation. This granularity can reveal fine-scale biomarkers, such as specific cell-stage markers that indicate a precise maturation stage. Proteomics and metabolomics are also advancing; combined with NGS, they provide a multi-dimensional view of reproduction. For instance, proteomic profiling of seminal plasma could identify new protein biomarkers predictive of sperm fertility. We foresee the development of biomarker panels identified by omics – sets of genes or proteins whose collective pattern can be computationally analyzed to give a "reproductive score." To manage the deluge of data from NGS, strong bioinformatics pipelines are essential. The trend is toward integrative analysis, where transcriptomic, proteomic, and epigenomic data are merged to pinpoint key drivers of reproductive success. The recommendation is that aquaculture research programs invest in building reference genomes and transcriptomes for key species, as well as longitudinal studies of gene expression across reproductive cycles, to fully leverage NGS for biomarker discovery and application.

- **Use of bioinformatics and artificial intelligence:** As datasets on reproductive genomics grow, bioinformatics and AI will be critical to extract actionable insights. Machine learning models can be trained on large datasets of gene expression (or DNA methylation, etc.) to predict outcomes like spawning success or embryo survival. For example, an AI model could analyze a complex expression profile from an ovary biopsy and output the probability that the fish will spawn within the next week or the expected fecundity. Already, advanced algorithms are used to find patterns in high-throughput data that humans might miss. Network analysis can identify regulatory hubs (key genes that control many others) which make good biomarker targets. If a transcription factor is found to coordinate many reproductive genes, monitoring that factor could be more efficient than tracking dozens of downstream genes. AI can also help in image-based biomarker detection – for instance, analyzing histological images of gonads to correlate with gene expression states (linking visual changes with molecular markers). In terms of recommendations, interdisciplinary collaboration is needed: reproductive biologists should work with data scientists to develop predictive models. A possible future scenario is an "Aquaculture Breeding Decision Support System" where an AI integrates biomarker data (gene/protein measures), environmental readings, and breeding history to advise when to induce spawning or which broodstock to pair. While these tools are nascent, their development should be prioritized, as they can greatly improve precision breeding. An important point is ensuring the quality and representativeness of data used – this means accumulating big data from diverse stocks and conditions so that AI models are robust. With proper validation, bioinformatics-driven biomarkers could reduce trial-and-error in hatcheries, moving towards a data-driven breeding approach.

- **Genetic editing in aquaculture breeding:** Technologies like CRISPR-Cas9 genome editing offer revolutionary possibilities for manipulating reproductive processes and establishing desired traits. In the context of biomarkers, once we identify genes critical for reproduction, genome editing can be used to validate their function and even create improved broodstock. For example, if a gene is linked to sex determination, CRISPR knockouts can confirm its role by observing if sex ratios change. This was demonstrated in several species: knocking out the foxl2 gene in XX tilapia caused functional males (confirming Foxl2 as a female pathway gene), and knocking out the dmrt1 gene in XY fish yields female development – such manipulations pave the way for mono-sex stock production without exogenous hormones. Likewise, CRISPR has been employed in Atlantic salmon to knockout the dnd gene, resulting in sterile fish that put all energy into growth (and also preventing invasive reproduction if they escape) (Qiao et al., 2024). For breeding, sterile fast-growing fish could be a boon. Gene editing can also directly introduce favorable alleles: for instance, if a variant of a fertility gene is known to enhance egg quality, CRISPR can be used to edit broodstock genomes to carry that variant. This is much faster than waiting for that allele to introgress via crossbreeding. In shellfish, where traditional breeding is challenging (Gjedrem & Rye, 2018), CRISPR could be used to produce lines with controlled breeding cycles (e.g., edit a photoperiod gene to spawn year-round). The combination of biomarker knowledge and gene editing is powerful – biomarkers tell us which genes are key leverage points, and CRISPR gives us the tool to tweak those points. Ethically and practically, the use of CRISPR in food species faces regulatory hurdles, but research is advancing. We recommend continued exploration of CRISPR for creating improved reproductive traits: examples might include editing hormone receptor genes to make fish respond to milder induction treatments, or knocking out inhibitory factors that delay maturation (Okoli et al., 2018, Zhu et al., 2024). Any such edits should be tested for off-target effects to ensure broodstock health. If regulations allow, genetically edited broodstock could dramatically reduce variability in reproduction (for example, generating lines that do not undergo unwanted early puberty or lines that produce only one sex). Even without creating a market animal, CRISPR-edited individuals can be used as research models to understand gene function, which in turn enriches biomarker development.

In summary, the future of aquaculture reproduction lies in harnessing technology to both understand and direct the biology. Next-gen sequencing will continue to reveal what biomarkers to look for, Artificial intelligence may help interpret them and make real-time decisions, and genome editing offers a way to act on that information by crafting better broodstock. For these advances to realize their potential, a few recommendations are clear: invest in genomic resources for aquaculture species, train personnel in bioinformatics and biotechnology, and establish regulatory frameworks for safe use of genome-edited fish and shellfish. By embracing these innovations, aquaculture can move towards more predictable and sustainable breeding – essentially, a future where we can precisely monitor and modulate reproductive processes for optimal output.

Conclusion

Reproductive biomarkers have become indispensable in modern aquaculture, encapsulating the intersection of molecular biology and breeding practice. They provide windows into the otherwise hidden workings of fish and shellfish reproduction – from the flurry of gene expression that drives gametogenesis, to the hormones orchestrating spawning, to the epigenetic marks left by environmental experiences. As reviewed, a variety of biomarkers (mRNA, protein, epigenetic) have been identified across aquaculture species, each illuminating a piece of the reproductive puzzle. Using these biomarkers, producers and researchers can achieve earlier and more accurate assessments of reproductive status, enabling timely interventions and selections that boost overall efficiency and yield. For example, transcriptional markers like Elovl4 and CYP4 in shrimp (Rottland et al., 2015) can predict fecundity, vitellogenin signals readiness of a fish to spawn or reveals endocrine disruption (Mahalingam & Santhanam, 2023), and miR-317/Dmrt4 interaction in mussels sheds light on gonadal development control (Wang et al., 2022).

The importance of these biomarkers extends beyond convenience – These can be defined as strategic tools for sustainable aquaculture. By detecting issues early (poor maturation, stress impacts, etc.), biomarkers help prevent wasted resources on failed breeding attempts. By guiding selective breeding (choosing inherently fertile and resilient breeders and producers), they contribute to genetic improvement while maintaining genetic diversity (since selection can be done more precisely, avoiding broad culling). And by monitoring stock health (e.g. seeing the molecular signs of overconditioning or senescence in broodstock), they inform best practices to prolong broodstock viability. All these applications align with sustainability: more output (fry, fingerlings) can be obtained with fewer inputs and less environmental impact when reproduction is well-controlled and efficient.

Looking ahead, strategic approaches for sustainable aquaculture breeding will heavily incorporate biomarker-driven methodologies. This includes establishing reference biomarker profiles for each species under optimal conditions, against which any deviation can be measured and corrected. It also means adopting the new technologies discussed: genomic and epigenomic tools to discover novel biomarkers and perhaps even breed for "biomarker-friendly" traits (like lines that have easily trackable markers of high fertility). An integrated framework might involve real-time PCR kits on the farm for key mRNAs, handheld biosensors for hormones, and cloud-based data systems that analyze trends across seasons and generations. The ultimate vision is an aquaculture industry where surprises in reproduction are minimal because we can foresee and manage reproductive states with scientific precision.

In conclusion, biomarkers bridge the gap between molecular-level understanding and practical aquaculture outcomes. They exemplify how fundamental science (gene expression, molecular endocrinology, epigenetics) can be translated into actionable techniques on the fish farm. By continuing to refine biomarker identification and usage – through next-gen sequencing, bioinformatics, and perhaps gene editing – we can greatly enhance broodstock management and breeding programs. The result will be not only higher productivity but also stability and sustainability: robust stocks that reproduce on cue, less reliance on wild seed, and the ability to adapt breeding programs in the face of changing conditions (climate, diseases, etc.) by monitoring the animals' own biological responses. As one study eloquently noted, a deeper understanding of molecular mechanisms of reproduction is fundamental to effective artificial breeding programs (Qiao et al., 2024). Biomarkers are the practical handle on those molecular mechanisms, and wielding that handle wisely is key to the future success of aquaculture.

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CHAPTER VI

SUSTAINABLE FEED: INSECTS, ALGAE, AND PLANT-BASED ALTERNATIVES IN AQUACULTURE

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Introduction

Aquaculture has become a vital element of the global food supply system, exceeding fisheries as the principal source of seafood for human consumption (Garlock et al., 2024. As aquaculture output escalates, the sustainability of aquafeeds emerges as a critical component in maintaining the environmental and economic viability of the business (Boyd et al., 2020. Aquafeeds representing a substantial segment of aquaculture operational expenses which are essential for the sustainability of aquaculture techniques and conventional formulations are predominantly dependent on limited marine resources. Growing demand for aquaculture feed exacerbates the strain on wild fish populations, occasionally resulting in the overfishing of essential fish stocks which indirectly jeopardizes the sustainability of marine ecosystems (Drillet, 2014. The swift growth of the aquaculture business has resulted in a significant rise in aquafeed production with forecasts suggesting an ongoing escalation to satisfy the needs of an expanding worldwide population (Burr et al., 2012. The industry's dependence on fishmeal and fish oil as principal sources of protein and lipids is an increasing problem, considering both resources originate from wild-caught fish (Muntean et al., 2024. Pelletier et al. (2009 assert that aquaculture feeds sourced from wild fisheries possess carbon intensities that may equal or surpass those of terrestrial meat production and overfishing associated with feed production intensifies ecological imbalance as well jeopardizes marine food webs. This reliance prompts concerns on the ecological impact of aquaculture, particularly given that a significant fraction of global fish stocks is already exploited or overexploited. This also supported by The Food and Agriculture Organization (FAO, 2020) where over 20 million tons of wild fish are harvested annually for reduction into fishmeal and oil. This extraction exerts considerable pressure on forage fisheries, which are essential not only for aquaculture feed but also as a food supply for marine predators and coastal residents. The price fluctuations of fishmeal and oil also influenced by climate change, regulatory limitations, and geopolitical instability which comprehensively threaten supply chain dependability and provide economic threats to aquaculture producers, particularly in developing countries (Tacon & Metian, 2015). Creating aquafeed leads to the loss of marine organisms which produces greenhouse gas emissions, causes pollution in the manufacturing process, and harms habitats used for getting the feed ingredients (Sarker, 2023). Therefore, researchers and farmers are paying extra attention to discovering new responsibly made feeds which reduces the pressure on seas and encourages more environmentally friendly ways of farming aquatic animals (Shati et al., 2022). It is important to focus on these matters for environmental protection, so the aquaculture industry continues to thrive and obey its obligations to society by meeting the world's growing need for protein (Riaz et al., 2024). The aquaculture sector is focused now on three main types of feed innovation: fishmeal from insects, ingredients made from algae, and protein from plants. They serve to help aquaculture become less dependent on scarce marine products and more economically and environmentally sound.

This chapter examines the studies on insect, algal, and plant-derived alternatives and evaluates their influence and function in aquafeeds. It consolidates significant research about various fish species, delineates optimal quantities for each category, and evaluates the primary benefits and drawbacks of each. The chapter aims to enhance and protect aquaculture by increasing its resource efficiency and environmental sustainability.

Insect-Based Feeds

People are showing more interest in insects being used in aquaculture feed, since they are good for nutrition and health of fish. Many researches have shown that relying on insects as food for animals can have positive effects on the environment and the economy since insects are a good source of protein (Usman et al., 2021). Lately, scientists have been researching if feeding aquaculture fish with insect meals could be a good substitute for fishmeal. Such nutritional benefits are found because organic food is greener, is more affordable, and provides extra vitamins (Abozaid et al., 2024). Many studies have been done on Black Soldier Fly (BSFL) larvae to see how they improve fish growth, better use feed, and raise the fish's immune response (Table 1). Feeding the larvae of the Black Soldier Fly (BSFL) to Nile Tilapia (*Oreochromis niloticus*), Atlantic Salmon (*Salmo salar*), and Rainbow Trout (*Oncorhynchus mykiss*) helped them grow well and eat their food with greater efficiency (Caimi et al., 2021; Limbu et al., 2022; Mazurkiewicz & Rawski, 2022).

Besides, the researchers discovered that BSFL administration enhanced the immune systems of Japanese Seabass (*Lateolabrax japonicus*) and Siberian Sturgeon (*Acipenser baerii*) (Wang et al., 2019; Rawski et al., 2020). As the percentage of inclusion rose above 75% lowers the benefits because the fillets became rich in unhealthy fat. In this way, the right amount of inclusion must be given so the fish's metabolism does not slow down. Yellow Mealworms (*Tenebrio molitor*) have been used often for studies, and their use in place of up to 50% fishmeal has made Rainbow Trout (*Oncorhynchus mykiss*) better in growth and ability to retain nutrients (Terova et al., 2021). The study revealed that if more than 75% of the diet consists of one type of food, it can lower the capacity of fish in digesting their feed, meaning proper balance of ingredients is needed. According to Basto et al. (2023), when Yellow Mealworm meal was added to the diets of European Sea Bass, it caused indigestion and led to increase on values of non-esterified fatty acids. It shows that proper care and knowledge about Yellow Mealworms' effects on fish are necessary.

Fishmeal can be replaced by another substitute known as House Crickets (Acheta domesticus). Perera et al. (2025) and Senanayake et al. (2025) revealed that changing from fishmeal to crickets did not harm the growth development, physical appearances, or survival of Guppy (*Poecilia reticulata*) and Swordtail (*Xiphophorus helleri*). Similar results were seen in Catla (*Catla catla*) as the optimal feeding of House Cricket did not alter growth or the feed conversion rate, showing it could be used in aquaculture (Perera et al., 2024). Even though research on Buffalo Worms (*Alphitobius diaperinus*) is not as common but they appear to have neutral impacts on fish growth and well-being. A study by Habte-Tsion et al. (2024) found that when feeding Buffalo Worms to Atlantic Salmon, growth parameters and feed efficiency were not changed as this indicate they can serve as functional feed for fish. However, more studies are required to learn the complete effects of Buffalo Worms on the digestive system of fish. The larvae of the housefly (*Musca domestica*) have shown they may improve the health and fertility of fish. Alofa et al. (2023) proved that Nile Tilapia consumption improved the conditions of various organs such as viscerosomatic and hepatosomatic indices. In the same way, giving African Catfish (*Clarias gariepinus*) maggot meal resulted in better gonad development, which makes it a possible additive to breeding rations (Ogunji et al., 2021). However, these findings suggest that Housefly larvae are more vital for managing health and immunity for aquatic fishes. Black Soldier Flies, Yellow Mealworms, House Crickets, and Houseflies are helpful insect-based feeds that support the growth, the efficiency of their diet, and the immune system of aquaculture species. However, it is important to choose these insects based on species-specific dietary needs and their overall health. Additional studies are required to improve number of insects in diets, study new types of insects, and examine how these feeds affect aquaculture over the long term.

Table 1. Insect-Based Feeds on Fish Species

No	Insect Species	Fish Species	Observation	Citation
1	Black Soldier Fly (*Hermetia illucens*)	Nile Tilapia (*Oreochromis niloticus*)	• Feeding Nile tilapia fry with meals of 81% to 84% BSFL meal enhanced growth performance. • The BSFL75 diet improved feed efficiency and did not adversely affect the liver or intestines	(Limbu et al., 2022)
		Atlantic Salmon (*Salmo salar*)	• The incorporation of Black Soldier Fly larvae (BSFL) meal in the diets of Atlantic salmon did not adversely impact growth performance. • An increase in the inclusion amount to 15% resulted in a reduction of the fillet fatty acid composition.	(Mazurkiewicz & Rawski, 2022)
		African Catfish (*Clarias gariepinus*)	• Replacing fish meal with BSFL meal at levels of up to 75% enhanced growth performance and feed efficiency in African catfish. • High inclusion levels (100%) led to diminished growth performance.	(Hervé et al., 2025)
		Rainbow Trout (*Oncorhynchus mykiss*)	• The substitution of fish meal with BSFL meal up to 15% did not negatively impact growth performance, fillet quality, or the health of the gastrointestinal tract and liver in rainbow trout.	(Caimi et al., 2021)
		Betta Fish (*Betta splendens*)	• Replacing 13% fish meal with black soldier fly larvae may enhance the growth performance, hematological parameters, and morphological characteristics of the liver and gut in *Betta splendens*.	(Kari et al., 2023)
		Japanese Seabass (*Lateolabrax japonicus*)	• Research on young Japanese seabass revealed that substituting fish meal with as much as 64% defatted BSFL meal enhanced growth performance, intestinal antioxidant activity, and immunological response. • Elevated inclusion levels may influence feed digestion.	(Wang et al., 2019)
		Siberian Sturgeon (*Acipenser baerii*)	• The incorporation of BSFL meal at levels up to 30% enhanced growth performance, feed acceptance, and feed efficiency without compromising nutrient digestibility.	(Rawski et al., 2020)
2	Yellow Mealworm (*Tenebrio molitor*)	Rainbow Trout (*Oncorhynchus mykiss*)	• The partial substitution of fishmeal with defatted Yellow Mealworm larval meal (up to 50%) enhanced growth performance and nutrient retention in rainbow trout. • Elevated inclusion levels (75% and 100%) resulted with decreased digestibility and growth performance.	(Terova et al., 2021)
		European Sea Bass (*Dicentrarchus labrax*)	• Substituting 50% did not negatively impact growth or hepatic health. • Total replacement (100%) resulted in elevated concentrations of non-esterified fatty acids and triacylglycerides, suggesting possible metabolic distress.	(Basto et al., 2023)
		Black Sea Bass (*Centropristis striata*)	• Substituting up to 25% of fishmeal led to markedly elevated weight-based specific growth rates in comparison to higher inclusion levels (75% and 100%).	(Redman et al., 2019)
		Largemouth Bass (*Micropterus salmoides*)	• An optimal amount (below 19.52%) in the diet can enhance development and bolster liver health.	(Chen et al., 2023)
3	House Cricket (*Acheta domesticus*)	Nile Tilapia (*Oreochromis niloticus*)	• The findings revealed that the specific growth rate (SGR) of the 100% house cricket meal diet was markedly lower than that of the control • Survival rates were comparable across all therapies.	(Perera et al., 2025)
		Guppy (*Poecilia reticulata*)	• The study found that replacing fishmeal with house cricket meal at 50%, 75%, and 100% levels did not adversely affect the growth performance or pigmentation of guppy fry, concluding that house cricket meal can fully replace fishmeal without negative effects.	(Senanayake et al., 2025)

		Swordtail (*Xiphophorus helleri*)	• A ten-week research on swordtail fry revealed that complete substitution of fishmeal with house cricket meal did not adversely affect growth performance or coloration, indicating its potential as a viable alternative to fishmeal in their diets.	
		Catla (*Catla catla*)	• An eight-week study on Catla fry showed that replacing fishmeal with field cricket meal at 35%, 70%, and 100% inclusion levels had no significant effect on growth performance or feed conversion ratio, • This indicating its potential as a complete fishmeal alternative in their diets.	(Perera et al., 2024)
4	Buffalo Worm (*Alphitobius diaperinus*)	Atlantic Salmon (*Salmo salar*)	• No differences were observed in growth, feed efficiency, or health markers. • Defatted mealworm meal fed fish showed higher plasma IgM (indicating immune enhancement) and gut microbiome shifts • Changes in *Pseudomonas* and *Tepidimicrobium* abundance.	(Habte-Tsion et al., 2024)
5	Housefly (*Musca domestica*)	Nile Tilapia (*Oreochromis niloticus*)	• The viscerosomatic and hepatosomatic indices in fish fed with alternative diets were considerably greater than those in fish fed with fish meal. • There is no substantial change regarding the growth index.	(Alofa et al., 2023)
		African catfish (*Clarias gariepinus*)	• Diets supplemented with maggot meal accelerated gonadal development and enhanced growth performance in fish.	(Ogunji et al., 2021)
		Gibel carp (*Carassius auratus gibelio*)	• Supplementing 390 grams of maggot meal protein per kilogram of basal food enhances the antioxidant capacity in gibel carp.	(H. H. E. Saleh, 2020)
6	Greater Wax Moth	Nile Tilapia (*Oreochromis niloticus*)	• Fish fed G. mellonella larvae (5–15% soybean meal replacement) had improved growth, feed efficiency, immune response, and cost savings compared to the control.	(Abozaid et al., 2024)

Algal-Based Nutrient

Algae are characterized by their quick growth rates, varied biochemical compositions and low land needs which offer a viable solution to these issues by providing a sustainable source of proteins and lipids for aquaculture feed (Shati et al., 2022). Algae's inherent nutritional density establishes them as essential components in aquatic food chains, making them ideal for aquaculture, particularly due to their ecologically sustainable and economically viable cultivation (Vijayaram et al., 2024). Microalgae are distinguished by their elevated crude protein content and amino acid profiles which are equivalent to fishmeal, rendering them a compelling alternative (Soma et al., 2024). The capacity of some algae species to amass significant amounts of lipids and proteins, surpassing 90% of their dry weight, highlights their potential as a rich supply of vital nutrients for aquaculture (Inuwa et al., 2022).

The inclusion of various algae species in fish feed has shown significant promise in improving the growth, immune response, and overall health of fish (table 2). The incorporation of *Spirulina platensis* at 5% and 10% (substituting 25% and 50% of fishmeal respectively) in Nile tilapia diets increased growth performance, elevated biochemical parameters, and strengthened immunological function, so affirming its potential as a fishmeal substitute (AlMulhim et al., 2023). Similarly, inclusion of *Chlorella vulgaris* in the diets of rainbow trout not only eradicated cadmium from liver and muscle tissues but also augmented antioxidant defences, boosted development, and fostered general health by rendering it a beneficial supplement in aquaculture systems subjected to contaminants (Harmantepe et al., 2024).

Another type of Algae, *Dunaliella salina*, has been examined to find out its effects on red tilapia and zebrafish. Red tilapia showed enhanced essential growth and better feed efficiency rate by consuming *D. salina*, proving it to be a good option for reducing usage of fishmeal (Mohammed, 2018). Mawed et al. (2022) found that adding *D. salina* to the diets of zebrafish has balanced their metabolism, reduced zinc-caused liver inflammation, and reduced genes related to gluconeogenesis and lipogenesis which indicating the importance of *D. salina* as immune when fish encounter environmental stressors. It has been proven that using the Eustigmatophyte Algae *(Nannochloropsis oculate)* to feed Nile tilapia and rainbow trout leads to better growth. Feeding tilapia with 5% *N. oculata* led to higher final weight and a faster specific growth rate (Abdelghany et al., 2020). In rainbow trout, replacing up to one-third of fishmeal with *N. oculata* improved growth rate and maintained the feed efficiency as well increasing the digestibility of EPA, showing the ingredient's functional benefits (Sarker et al., 2020). Other species of green algae called *Scenedesmus dimorphus* was included in rainbow trout diets, causing changes in the fatty acids found in their livers which polar phospholipids increased more than triacylglycerols, suggesting an improvement in lipid metabolism and nutrition that could boost the fish's general health (Skalli et al., 2020).

Tetraselmis suecica in dried form was tested in European sea bass and it was found that fish can benefit from up to 20% fish protein replacement without compromising their dietary performance or impacting their growth. Hence, *T. suecica* could be a helpful part of carnivorous fish diets because it helps reduce the amount of fishmeal needed for protein (Tulli et al., 2012).

The study discovered that feeding the Nile tilapia blue-green algae (*Phaeodactylum tricornutum*) enhanced their growth, boosted their defences with higher antibacterial serum, and stimulated important genes related to growth (Abdel-Tawwab et al., 2024). Therefore, it helps ensure the best growth and better health in fish farming. Feeding zebrafish with a mixture of up to 50% Green Algae (*Chlamydomonas reinhardtii*) did not harm them in any way. It was found that giving mealworms as a regular feed to aquatic fish can reduce environmental effects and improves both growth and feed efficiency. This could suggest that mealworms can be used as a new feed ingredient instead of others (Darwish et al., 2023).

Pompano, red tilapia, and European sea bass fish feed on the algae species known as *Isochrysis galbana* in the diet. Feeding pompano with diets of 4.5–5.0% *Isochrysis galbana* made them develop faster and raised the amounts of n-3 LC-PUFAs in their fillets (He et al., 2018). Having just 5% of the component added to red tilapia's diet enhanced their immune system and raised the levels of serum bactericidal and lysozyme, proving that it is beneficial to their immunity (Bustamam et al., 2022). No decrease in growth or efficiency of feed was noticed as fish protein in European sea bass was replaced with *Isochrysis galbana* up to 20% (Undeland, 2012). The studies confirm that *Isochrysis galbana* helps improve the nutrition in fish feed and increases the fish's immunity. According to Ali et al. (2024), the involvement of 10% red algae *Gracilaria sp.* in their diet increased the growth rate, body weights, and protein in the carcass of silver carp compared to the control group,. In a similar way, the exposure of *Gracilaria sp.* to Persian sturgeon raises blood protein and albumin levels, as well as increases the activity of lysozyme in the skin mucus. According to these results, *Gracilaria sp.* can promote the development and immunity in fish, explaining why it is considered a valuable ingredient for fish farming (Adel et al., 2021).

Therefore, the inclusion of diverse algae species in fish diets not only augments growth performance but also bolsters immunological responses, detoxifies toxic compounds, and alters lipid metabolism, rendering them viable and sustainable alternatives to conventional fishmeal and fish oil. The potential of algae like *Spirulina platensis*, *Chlorella vulgaris*, *Dunaliella salina*, *Nannochloropsis oculate*, *Tetraselmis suecica*, *Phaeodactylum tricornutum*, *Chlamydomonas reinhardtii*, *Isochrysis galbana*, *Scenedesmus dimorphus*, and *Gracilaria sp.* to improve aquaculture nutrition supports their role in fostering more sustainable and environmentally-friendly practices in the industry.

Table 2. Algae-Based Feeds for Fish Species

No	Algae Species	Fish Species	Observation	Citation
1	Cyanobacteria (*Spirulina platensis*)	Nile Tilapia (*Oreochromis niloticus*)	• The inclusion of probiotic *Spirulina platensis* at 5% and 10%, replacing 25% and 50% of fishmeal, improved growth performance and influenced biochemical parameters in the diets.	(AlMulhim et al., 2023)
2	Green Algae (*Chlorella vulgaris*)	Rainbow Trout (*Oncorhynchus mykiss*)	• The incorporation of algae eliminated Cadmium from liver and muscle tissues • Enhanced the parameters of the antioxidant defence system and promoted development.	(Harmantepe et al., 2024)
3	Green Algae (*Dunaliella salina*)	Red Tilapia (*Oreochromis spp.)*	• Substituting 33% of fish meal with *D. salina* can improve growth and feed efficiency without adversely affecting fish health.	(Mohammed, 2018)
		Zebrafish (*Danio rerio*)	• *D. salina* supplementation reinstated metabolic equilibrium and mitigated hepatic inflammation caused by zinc exposure. • Regulated gene expression associated with gluconeogenesis, lipogenesis, and inflammatory reactions.	(Mawed et al., 2022)
4	Eustigmatophyceae (*Nannochlor*	Nile Tilapia (*Oreochromis niloticus*)	• Notable augmentation in final weight and specific growth rate in the 5% inclusion group relative to the control. • The activities of liver enzymes (alanine transaminase and aspartate transaminase) were not substantially influenced by dietary supplementation.	(Abdelghany et al., 2020)

		Rainbow Trout (*Oncorhynchus mykiss*)	• Diets including up to 33% fishmeal substitution exhibited similar growth, feed conversion efficiency, and survival rates as the control diet. • Elevated digestibility of eicosapentaenoic acid (EPA) and lysine in the co-product.	(Sarker et al., 2020)
5	Green Algae *(Tetraselmis suecica)*	European Sea Bass (*Dicentrarchus labrax*)	• *Dried T. suecica* could substitute up to 20% of fish protein in European sea bass diets without negatively impacting growth performance and fillet quality.	(Tulli et al., 2012)
6	Diatom *(Phaeodactylum tricornutum)*	Nile Tilapia (*Oreochromis niloticus*)	• Substantial improvement in growth indicators at 15 g/kg incorporation. • Increased serum bactericidal activity against *Aeromonas sobria*. • Enhanced activity of antioxidant enzymes. • Upregulation of genes for growth hormone (GH) and insulin-like growth factor (IGF-1).	(Abdel-Tawwab et al., 2024)
7	Green Algae *(Chlamydomonas reinhardtii)*	Zebrafish (*Danio rerio*)	• Substituting 20% of fishmeal with *C. reinhardtii* biomass yields ideal outcomes • 10% substitution still delivers considerable advantages. • A 50% replacement is both practical and advantageous which can function as a sustainable feed supplement and alternative in aquaculture.	(Darwish et al., 2023)
8	Haptophyte Algae *(Isochrysis galbana)*	Pompano *(Trachinotus ovatus)*	• Integrating around 4.5–5.0% boosted growth performance and elevated the concentrations of omega-3 long-chain polyunsaturated fatty acids (n-3 LC-PUFAs), notably docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) in the fish fillet and live specimens.	(He et al., 2018)
		Red Tilapia (*Oreochromis spp.)*	• 5% *Isochrysis galbana* shown an enhancement in innate immune responses. • The research indicated enhanced serum bactericidal and lysozyme activities	(Bustamam et al., 2022)
		European Sea Bass (*Dicentrarchus labrax*)	• Substituting 10% and 20% of fish protein with dried *Isochrysis galbana* did not negatively impact fish growth or feed efficiency.	(Undeland, 2012)
9	Green Algae *(Scenedesmus dimorphus)*	Rainbow Trout *(Oncorhynchus mykiss)*	• Supplementation with *Scenedesmus sp.* modified hepatic lipid composition. • Increases polar phospholipids in comparison to triacylglycerols, presumably due to alterations in lipid metabolism.	(Skalli et al., 2020)
10	Red Algae *(Gracilaria sp.)*	Silver Carp *(Hypophthalmichthys molitrix)*	• Incorporating 10% *Gracilaria sp.* into the diet markedly improved mean weight gain, specific growth rate, feed conversion ratio, and carcass protein and fat content relative to the control group.	(Ali et al., 2024)
		Persian sturgeon *(Acipenser persicus)*	• The total protein and albumin levels in the blood considerably elevated in fish administered 5 and 10 g/kg ($P<0.05$). • The concentrations of total protein and lysozyme activity in the skin mucus were markedly elevated in the blood and fillet of the fish.	(Adel et al., 2021)

Plant-Based Alternatives

Utilizing plant-based ingredients in aquaculture feeds indicates that aquaculture is becoming more environmentally friendly by relying less on wild marine creatures and reducing the negative effects of standard feed ingredients (Akter et al., 2024). The higher costs and decreasing supply of fishmeal are leading to more use of plant-based components in aquaculture diets, and this situation is causing researchers to investigate new alternatives as soon as possible (Chepkirui et al., 2022). According to Hussain et al. (2024), Soybean meal, canola meal, and grain-based items are effective as well as available alternatives to fishmeal in aquafeeds.

Introducing plant-based materials into aquaculture feeds has greatly contributed to more sustainable methods of fish farming (Table 3). Research findings indicates that adding soybean meal agon can replace as much as half of fishmeal used in tilapia (*Oreochromis niloticus*) feeds with no impact on their development or condition (Ahmad et al., 2020). In the same way, using 10% to 20% corn gluten meal (CGM) in place of fishmeal in the diets of rockfish (*Sebastes schlegelii*) was shown by Zaman and Cho (2025) to have little impact on growth performance, the amount of feed conversion, and feed efficiency. It proves that CGM and similar additives can be used well in aquaculture without causing problems in key areas of performance. It was also proven that rainbow trout (*Oncorhynchus mykiss*) could be fed diets with up to 8% canola meal as a substitute, with little effect on lipid digestion or signs of growth, meaning that low substitution is possible for sustainable reasons (Yigit et al., 2012). Rainbow trout (*Oncorhynchus mykiss*) grow better when they are fed lupin meals, so it can be used as a viable protein resource (Glencross et al., 2011). Experts also examined the possibility of using rapeseed meal instead of fishmeal when creating the feed for rainbow trout (*Oncorhynchus mykiss*). It was revealed in studies that rapeseed protein isolate can replace around 68% of fishmeal in feed without having a negative effect on animals' health or their growth (Kaiser et al., 2021). In fact, using 30% PPI in fish feed did not affect tilapia growth and succeeded in lowering the crude ash level in the fish (Schulz et al., 2007).

Scientists also looked at white seabream (*Diplodus sargus*) after feeding them wheat gluten. Transferring up to 30% of wheat gluten for fishmeal did not change the rate at which fish developed (Saleh et al., 2021). It was found that Nile tilapia (*Oreochromis niloticus*) keeps similar growth rates whether fishmeal or rice bran is provided in their diet, which makes rice bran a good economical alternative (Muin et al., 2014). It is also established from research that including 10% Moringa in the diet of ray-finned fish (*Cirrhinus mrigala*) aids the environment, supports the circular economy, and boosts the sustainability of aquaculture practices (Tabassum et al., 2025). Fish fed 10% duckweed (*Lemna minor*) tended to experience mild improvements in fertilization, hatching, and survivability, thus suggesting its usefulness as a feed for animals in fish farming (Achoki et al., 2024). Li et al. (2023) revealed that adding 17.2% cottonseed meal to the diet aided the growth of red-tailed catfish, lowered feed expenses, enhanced digestion, improved protein metabolization, and maintained the fish's antioxidant activity.

In summary, replacing regular ingredients in fish feed with soybean meal, corn gluten meal, lupin meal, rapeseed meal, pea protein isolate, wheat gluten, rice bran, Moringa oleifera, duckweed, and cottonseed meal can improve the sustainability of aquaculture. These ingredients promote similar improvement, eating habits, and well-being for fish as traditional fishmeal at a better price and with less damage to the environment. The transition decreases our usage of resources from the ocean and lessens the negative effect of aquaculture feed production on the environment.

Table 3. Plant-Based Feed on Fish Species

No	Plant - Based	Fish Species	Observation	Citation
1	Soybean Meal	Nile tilapia (*Oreochromis niloticus*)	• Incorporating 50% soybean meal into the diet can replace fishmeal without compromising the development and health of Nile tilapia.	(Ahmad et al., 2020)
2	Corn Gluten Meal (CGM)	Rockfish *(Sebastes schlegeli)*	• Fishmeal (FM) in rockfish diets can be substituted with up to 10% to 20% of CPC without markedly affecting weight gain, feed conversion, specific growth rate, or feed efficiency.	(Zaman & Cho, 2025)
3	Canola Meal	Rainbow trout *(Oncorhynchus mykiss)*	• No substantial variations in lipid digestibility or somatic indicators were observed ($P > 0.05$). • Canola meal may substitute for regular diets by up to 8% in rainbow trout fry without negatively impacting performance.	(Yigit et al., 2012)
4	Lupen Meal	Rainbow trout *(Oncorhynchus mykiss)*	• The inclusion of all types of lupin meal was seen to enhance fish growth throughout the treatments.	(Glencross et al., 2011)
5	Rapeseed Meal	Rainbow trout *(Oncorhynchus mykiss)*	• The protein absorption of the rapeseed isolate of protein reached 95.2%, therefore as much as 68% of nutritional fishmeal could be substituted without significantly impacting growth or health metrics.	(Kaiser et al., 2021)
6	Pea Protein Isolate (PPI)	Nile tilapia (*Oreochromis niloticus*)	• The presence of 30% pea protein isolates in the diet sustained similar growth performance while decreasing crude ash content in fish body composition, with no significant variations noted in crude protein or lipid levels among dietary groups.	(Schulz et al., 2007)
7	Wheat Gluten	White Seabream *(Diplodus sargus)*	• wheat gluten can substitute for fishmeal protein by up to 30% in diets for white seabream.	(N. E. Saleh et al., 2021)
8	Rice Bran	Nile tilapia (*Oreochromis niloticus*)	• Diet with complete substitution of rice bran with mushroom stems indicated that there was no statistically significant difference ($p>0.05$) regarding growth performance and feed utilization	(Muin et al., 2014)
9	Moringa Oleifera	Ray finned fish *(Cirrhinus mrigala)*	• Inclusion of 10% in *C. mrigala* diets is best for environmentally sustainable and economically efficient aquaculture.	(Tabassum et al., 2025)
10	Duckweed (*Lemna minor*)	Nile tilapia *(Oreochromis niloticus)*	• The incorporation of *L. minor* in the diets led to marginally improved fertilization, hatchability, and survival rates at 10%.	(Achoki et al., 2024)
11	Cottonseed Meal	Red-Tailed Catfish *(Hemibagrus wyckioides)*	• An inclusion level of 17.2% enhanced the growth rate, feed cost efficiency, gastrointestinal function of enzymes, and protein metabolism, while maintaining antioxidant capacity.	(Li et al., 2023)

CONCLUSION

The transition to sustainable feed innovations in aquaculture is crucial to tackle the increasing environmental and economic difficulties associated with conventional fishmeal and fish oil. Rising worldwide demand for products from aquaculture farms is making it more important to come up with sustainable ways to add protein to these diets. Using feeds made from insects such as Black Soldier Fly, Yellow Mealworm, House Cricket and others seem to help fish maintain their performance and health while switching away from fishmeal. Using these methods helps the environment and protects overharvested resources in the sea.

Utilizing algal proteins and lipids in diets can add significant variety to fish farming, giving them both better nutrition and better environmental outcomes which emphasize on important of fatty acids DHA and EPA. Microalgae can be farmed in supervised settings, so they act as a good and natural source of food for fish and other sea creatures. Similarly, soy, pea, lupin, and canola have been looked into for their health benefits, but issues with anti-nutritional elements must be fixed to increase their popularity. Investigating the combination of insect, algal, and plant-based ingredients shows that they together can strengthen the nutritional value of aquafeeds. Collaborating in this way can reduce the expenses associated with production and have low negative effects on the environment. Nevertheless, these various alternatives still face obstacles, such as obtaining permission from regulators, handling technology problems, and gaining customer approval. New studies are needed to address these problems, as incorporating synthetic biology and precision technology in aquafeeds may lead to more sustainable, cost-efficient, and scalable methods in the industry. In conclusion, using these new feed resources will be necessary to secure the industry’s success, protect the environment, and meet the overall goals of sustainability in aquaculture.

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CHAPTER VII

DIGITAL TECHNOLOGIES AS A MEANS OF SUSTAINABLE DEVELOPMENT OF AQUACULTURE (CASE OF AZERBAIJAN)

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Introduction

The strategic nature of digital technology stems from its ability to transform all areas, including the area of water cycle management. Digital technologies represent a profound change in the design of integrated control networks and in the way they are used in different ways, eliminating difficulties in levels of integration. The implementation of scenarios 5G and other cybernated devices in the development of aquaculture as well as in the development of smart fish farms is becoming more and more relevant. The hyper-flexibility of digital technologies give a chance for Caspian countries. At the heart of innovative fish farming is the principle of artificial intelligence management. Caspian region directions in promising aquaculture requires more active participation and mutually beneficial cooperation of all parties.

The beginnings of artificial fish farming in Azerbaijan date back many years. The work on artificial and natural breeding of various fish species in Azerbaijan began in the early 20th century and has been scientific in nature. The history of artificial fish farming in Azerbaijan is associated with the name of the outstanding Russian researcher Alexander Nikolaevich Derzhavin.

The Origins of Artificial Fish Farming in Azerbaijan Date Back Many Years

The promising scientist's journey to the Caspian Sea began between 1910 and 1912, when he worked as a biologist at the Astrakhan Ichthyological

Laboratory. This marked the first stage of his activity focused on studying fish and invertebrates inhabiting the Caspian Sea. During these years, A. N. Derzhavin studied the biology of certain trout species and their migrations into the Volga River, as well as the feeding behavior of trout, bream, and herring. He collected a wealth of material for several works on the relict fauna of the Caspian Sea in the lower Volga region. At this stage, the scientist also described a new species of jellyfish and sand crab that appeared there.

Caspian Sea researcher's work second stage lasted much longer. He came to Baku in 1912 and continued his scientific research until 1927. Derzhavin established an Ichthyological laboratory in Baku under the Department of Agriculture - now known as the Azerbaijan Scientific Research Institute of Fisheries and became its first director. This laboratory carried out comprehensive studies of the Ichthyofauna of the Caspian Sea.

A. N. Derzhavin led the Baku Ichthyological Laboratory for 15 years and during that time conducted extensive research on the biology of sturgeon and Caspian salmon living in the Caspian Sea. Derzhavin also established stationary research stations in the Kura River basin and organized the artificial reproduction of valuable fish species such as sturgeon, long-nosed sturgeon, salmon, and kutum.

The establishment of fish farms and settlements in Mingachevir, Garadonlu, Banka, as well as on the Samur and Sulak rivers, was the result of A. N. Derzhavin's organizational talents. He developed methods for fertilizing sturgeon roe by first washing it with silt and then incubating the fertilized eggs in the Ses-Green apparatus. Thus, A. N. Derzhavin laid the foundation for the method of removing adhesive surface from sturgeon eggs, thereby enabling their artificial reproduction (Akhundov 2011:239).
Potential changes in the fisheries of the Kura River were among the great scientist's main concerns. Derzhavin had seen the state of the Kura 50–60 years ago. In one of his discussions, he stated that the construction of the Mingachevir Dam had dealt such a severe blow to Kura fisheries that they would never fully recover. He saw the only solution to these problems in the

expansion of artificial fish-breeding networks and in the final years of his life, his work was primarily focused in that direction (Akhundov, 2011: 108).

Modern State of Fishery Management in Azerbaijan

At the present stage, responsible for cultivation, restoration is government bodies. Development department of biological resources in water basins manages cultivation. Systematic research on marine biological resources is conducted by the Azerbaijan Scientific Research Institute of Fisheries.

Biological resources department of water basins fulfils the functions of restoring and increasing the populations of important fish species inhabiting the waters, rivers, and inland bodies of the sea. Its aim maintaining their gene pool and biodiversity (Akhundov, 2013: 93).

If we look at the world's leading countries in fish production, China is in first place. Of course, fishing in Azerbaijan is not as widespread as in China, but in recent years, various measures have been taken in the country to increase fish production. When we examine Azerbaijan's fishing industry, we undoubtedly notice the production of caviar. Just the same, we see the development in this direction. Fish farms are being established across the country, and fish hatcheries and processing facilities are growing day by day.

Azerbaijan has become a participant in a food and agriculture initiative carried out within the FAO–Turkey Partnership Programme, called 'Capacity Building for Sustainable Fisheries and Aquaculture Management in Central Asia, Azerbaijan, and Turkey.

Supported by funding from the Government of Turkey, the FISHCap project focuses on enhancing the sustainable use, management, and conservation of natural resources by promoting the development of fisheries and aquaculture. With a total budget of $1 million, the initiative was planned for implementation through 2022. Alongside Azerbaijan, participating countries include Kazakhstan, Kyrgyzstan, Tajikistan, Turkey, Turkmenistan, and Uzbekistan.

FISHCap assists partner governments in effectively applying integrated water resource management strategies to promote rural economic growth, enhance food security, create employment opportunities, and reduce poverty. This is achieved by building institutional capacity and offering technical support for the sustainable advancement of national aquaculture resources.

Additionally, the country participated in projects implemented in 16 countries as part of the first phase of the partnership program from 2009 to 2015 (Interfax Azerbaijan).

Similar to Russia and the Central Asian nations, Azerbaijan relies heavily on the Caspian Sea for its fish production, which serves as the country's primary fishing area.

Being the second-largest body of water after the Persian Gulf in terms of energy resource reserves the Caspian Sea has a rich flora as well as energy and natural resources. The Caspian Sea is abundant in various seafood and is home to 101 species of fish. Indeed, fishing in the Caspian Sea is not limited to its waters alone. The Kur River, other sources of freshwater in the country, and fish farms established in recent years meet the country's fish needs. Subsequent to the regulation of the Kura and Aras river systems in the mid-20th century, natural spawning grounds for many valuable fish species were left in the upper reaches of the dams, consequently limiting the natural reproductive capacity of these fish. This, in turn, created a need for their artificial reproduction. Therefore, in 1952, the construction of artificial fish farms was initiated in the republic (Mammadov, et al., 2011:96).

Over the past fifty years, the systems and technologies used in aquaculture production have rapidly evolved. They range from very simple devices to high-tech systems. Table 1 illustrates some methods that will contribute to the progressive and sustainable development of aquaculture in Azerbaijan through the exchange of science, technology, education, and information.

The study reveals that digital technologies hold significant potential to enhance the sustainability of aquaculture in Azerbaijan. Key findings indicate that tools such as remote sensing, data analytics, automated feeding systems, and environmental monitoring contribute to improved productivity, resource efficiency, and environmental protection. However, the integration of these technologies remains limited due to challenges such as lack of infrastructure, digital literacy, and access to financing.

Table 1. Methods for Progressive and Sustainable Development

1	Development and promotion of fisheries at the educational, scientific and technological level.
2	To collect and disseminate technical and other information in the field of fisheries.
3	Meetings for the presentation, exchange and discussion of information, results and experiences on all topics and methods of fisheries.
4	To promote training in all stages of fisheries and the training of professionals involved in aquaculture.
5	To promote scientific research and educational activities in the field of fisheries in cooperation with public institutions both at national and international levels.

Source: Compiled by the author based on data from the World Aquaculture Society

Interviews and case analyses suggest that successful implementation depends on stronger collaboration between government agencies, research institutions, and private sector stakeholders. Moreover, increasing awareness and capacity-building programs for local producers are essential for driving digital adoption.

The discussion highlights that digitalization not only optimizes farm operations but also aligns with national goals for food security and sustainable rural development. If adequately supported, digital transformation in aquaculture could position Azerbaijan as a regional leader in sustainable aquatic food production.

The primary goal of expanding the fisheries industry is to raise the production of aquatic products without a significant increase in the use of water and key natural land resources. The second goal is to establish environmentally friendly aquaculture systems that support long-term sustainability. Yet to create systems that ensure fair value, meaning profit, to support economic and social sustainability. These three core conditions for sustainable fishery development can be met through biotechnology.

In the coming decades, fisheries may face numerous challenges, particularly diseases and epidemics. Alongside the development of appropriate feeding mechanisms, exploration technologies, and management practices, water quality management is also an important factor for the development of fisheries. These cover all key domains of biotechnology along with other technological innovations. Aquatic biotechnology refers to the scientific use of biological principles aimed at boosting productivity and economic efficiency in multiple industrial fields (Ikenoue, et al., 1992: 93).

The Convention on Biological Diversity refers to biotechnology. Biotechnology includes a wide range of approaches aimed at improving living conditions, production, and management of commercial fisheries. While some biotechnologies are modern and innovative, others have been used for a long time, such as fermentation and pond fertilization to enhance their nutrient capacity.

Numerous modern biotechnological advancements stem from the rapidly progressing understanding of molecular biology and genetic science. Basic biotechnology in fisheries sector is analogous to the biotechnology utilized in agriculture.

Biotechnological innovations

The evolution of data necessary to optimize secure biotechnological innovations in fisheries is particularly important and faces several challenges stemming from the diverse production methods tailored to different aquatic species. The primary reason for transferring all technology to the fisheries sector is that it must be utilized considering the unique aquatic biodiversity and the specific living conditions of the rural population, along with the potential economic impacts. Contributions to biotechnology and supplies shield, deprivation reduction, profit growth boosting, and must be prepared to address these challenges and responsibly develop these technologies (Ikenoue, et al., 1992: 127).

The application of genetic principles to enhance aquaculture production currently lags significantly behind that of crop and livestock production. Only a small portion of aquaculture species undergo genetic development programs, yet biotechnology and genetics hold tremendous potential for increasing production and enhancing ecological sustainability.

Biotechnology offers tools to rehabilitate organisms raised in aquaculture and boost early developmental success. It also creates opportunities to enhance reproduction, growth, and survival rates of endangered species, thereby supporting the conservation of aquatic biodiversity. Transgenic technologies have the potential to improve growth rates, market size, nutrient composition, disease resistance, and tolerance to harsh environmental conditions. However, the application of transgenic organisms in fisheries remains controversial, making consumer education and acceptance critical (Davis, 2015: 37).

Biotechnological methods can also be applied to detect and analyze important aquatic germplasm resources, including those of endangered species. Research in biotechnology aids in understanding gene regulation and expression, sex determination, as well as the identification of species, genetic resources, and populations. In recent years, aquaculture has been included in research on more productive feeding methods. An underwater video monitoring system is used to record when fish are satiated, allowing feeding to be halted and monitoring waste accumulation beneath closed cages (Davis, 2015: 65).

Biotechnology is a method of improving water quality in the cultivation of aquatic products by balancing carbon and nitrogen in the system. Recently, this technology has attracted attention as a sustainable method for managing water quality.

When carbon and nitrogen are well-balanced solutions, ammonium is converted into bacterial biomass in addition to organic nitrogenous waste. Adding carbohydrates to ponds stimulates the growth of heterotrophic bacteria, while nitrogen is obtained from the production of microbial proteins. Biotechnology contributes to improved water quality by introducing extra carbon into the aquaculture system, either through external carbon sources or by utilizing bait with a high carbon content.

Biotechnology allows for minimal water exchange and usage by maintaining proper water quality in the culture unit, producing low-value bioblocks rich in protein that can serve as feed for irrigating organisms.

Compared to traditional water purification technologies used in biological water supply technologies, this is a more economical alternative (reducing water purification costs by 30%) and additionally offers potential cost savings on feed (protein utilization efficiency is twice that of traditional pond systems in biotechnology). This represents an inexpensive and sustainable structure for irrigation development (Davis, 2015: 79).

When creating biotechnology in fish farming ponds, a certain initial period is required to establish a well-functioning water quality management system, which is based on nitrogen and organic loading in aquaculture water and, therefore, on the intensity of the system. Similarly, it takes about 4 weeks, depending on nutrients, water ratio, and temperature, to form the necessary microbial community in the biofilter.

However, since heterotrophs in biofilters outnumber nitrifying bacteria by a factor of 10, the biotechnology system can generally be established faster than in traditional biological filters. Biological technologies can also be used to overcome the low-temperature cycles in winter, provided that proper water temperature, good water quality, and water-saving conditions in greenhouses are maintained.

Experience and technical knowledge in biotechnology should be communicated to farmers in a clear, practical, and simple manner. An essential aspect of applying fishery technologies in aquaculture is the monitoring of ponds. Biotechnology is still not entirely predictable, so its implementation at the farm level can carry certain risks. Most aquatic production worldwide is carried out in semi-intensive and extensive systems. However, there is increasing interest in high-tech aquaculture systems in response to growing demand.

Biotechnology offers effective solutions for promoting sustainability in fisheries, aquaculture, and the broader food industry. As consumer demand for seafood continues to rise and natural marine resources decline, researchers are increasingly turning to biotechnological innovations to enhance seafood production. Biotechnology offers aquaculture, fisheries, and the food industry effective solutions for sustainable growth. Scientists are studying genes that can promote natural fish growth and help resist infections. Various techniques are used globally to improve fish feeding efficiency. For example, in Japan, aquaculture enterprises use small sound signals to attract fish during feeding. This significantly improves feeding efficiency, reducing feeding time from 20 minutes to just 5 minutes (Ikenoue, et al., 1992: 54).

Aquaculture is conducted based on biological and technological justifications in fishery water bodies. The procedure for conducting aquaculture is determined by the relevant executive authority. The biological and technological justification prepared by aquaculture entities for carrying out activities in fishery water bodies must be registered as per the guidelines issued by the appropriate governing authority. A state fee is charged for registering such justifications.

The purpose of the aquaculture farm, layout scheme, fish species and other aquatic biological resources that are necessary and have been adapted for the activity, their biological characteristics and sources, the technologies applied, reclamation works, and fish production volumes should be included in the biological and technological justification. It must also reflect the characteristics of the reservoir, water volume, fish productivity of the site, energy costs, types of feed used, and the types and quantities of waste (Davis, 2015: 73).

Biological and technological justifications are valid for 25 years for sturgeon species and 10 years for other fish and aquatic biological resources. If there are any changes in the direction of aquaculture, restructuring, or expansion of the farm, appropriate changes must be made to the justification and must be informed (Mammadov, et al., 2013: 125).

In Azerbaijan, a closed water supply system is primarily used for fish and other aquaculture products. Let us examine the application of the closed water supply system using the example of the Khillyinskoe Sturgeon Farm. For the cultivation of larvae, plastic round pools with a diameter of up to 2 meters and concrete pools with a diameter of up to 4 meters are used. Fish are raised in these ponds until they reach a weight of 100 gram and are then released at the mouth of the Kura River using trucks designed for transporting live fish. Fertilized fish eggs are placed in special incubators. Depending on the species of fish and the water temperature, larvae are produced from these eggs within a period ranging from 3 days to a week. These larvae are collected in collecting ponds and are regularly harvested and transported to the plastic round water bodies.

In recent years, considerable focus has been directed toward the advancement of pond-based fisheries at various regions of the country. Favourable conditions have been created for the revival of this industry in areas where mountain rivers flow. High-yield fish are bred in the artificial lakes created. Farms engaged in pond fishing have already been established in different villages. These artificial lakes, covering an area of about 4 hectares, are populated with fry. Farmers involved in pond fishing primarily prefer carp, white amur, and wild fish. They believe good results can be achieved in this field if the conditions for fish maintenance and feeding are properly organized. At the same time, both local and foreign experiences are being studied to promote the development of pond fishing. Fish can be cultivated not only in ponds but also in seas and rivers.

According to experts, it is important to build hatcheries in the regions for the cultivation of fry. Farmers interested in this industry should bring fry from Neftchala.

Numerous natural and anthropogenic factors damage coastal landscapes, habitats, economically important resources, and infrastructure. Natural factors include fluctuations in sea level, storm surges, and earthquakes. Anthropogenic factors encompass desertification/deforestation, river regulation, trends in city expansion and industrial growth, poorly structured planning and development efforts of agricultural/aquaculture activities, insufficient groundwater management, the development of the recreational sector, and pollution from land and sea sources. Climate change intensifies the effects of both natural and human-induced factors, leading to considerable socio-economic harm in coastal regions. In the Caspian Sea area, up to 40% of coastal zones are impacted, with an estimated 69% experiencing varying degrees of desertification. Unregulated coastal development, along with environmental pollution and the reduction of fish stocks, has negatively influenced public health. To effectively address these challenges, a thorough understanding of integrated planning and coastal land use management is essential. (Framework Convention for the Protection of the Marine Environment of the Caspian Sea, Annex 2, p. 21-33).

Rational Use of Biological Resources

- Implementation of activities for the protection, restoration, and conservation of biological resources;
- Promotion of regional cooperation and improvement of the efficiency of fish farming enterprises, including scientific exchange;
- Development of aquaculture and establishment of a gene bank for fish species;
- Assessment of opportunities for formulating and adopting additional protocols to the Tehran Convention, in line with the provisions of Article 14;

- Improvement of national mechanisms for the implementation and enforcement of national legislation and relevant multilateral environmental agreements concerning the protection of biological resources.

Conclusion

The Caspian region faces challenges stemming from the unsustainable development of its coastal zones, driven by a range of factors affecting the population, environment, and infrastructure. Coastal landscapes and ecosystems are being degraded by both natural and human-induced influences. Natural drivers include fluctuations in sea level, seismic activity, and the effects of climate change. On the human side, contributing factors encompass desertification, deforestation, river flow modification, urban and industrial expansion, inadequate planning in agriculture, aquaculture, and tourism development, along with pollution originating from land-based and marine sources (Annex 2, 22).

Aquatic biotechnology and other technological advancements play a vital role in improving aquaculture performance, attracting investment, and promoting international collaboration in technology transfer. Advancing biotechnology in the fisheries sector can support the sustainable production of healthy, fast-growing aquaculture species with minimal environmental impact. However, progress in this field largely hinges on the willingness of producers to engage with scientists and collaborate with international donors to support research, capacity building, and infrastructure development in emerging economies. Strengthening the exchange of information and fostering dialogue among scientists, researchers, and producers across various regions will significantly contribute to the growth of this critical sector, ultimately supporting the expansion of sustainable aquaculture in Azerbaijan.

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CHAPTER VIII

CURRENT SITUATION AND RECENT ADVANCEMENTS OF THE AQUACULTURE SECTOR IN TÜRKIYE

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Introduction

Türkiye is a peninsula with many natural lakes, dam lakes, ponds, reservoirs, rivers and streams. This diversity in water resources offers significant potential for aquaculture (Figure 1).

Figure 1. Türkiye view from the space.

In addition, the country has 8.333 km of coastline and 177.714 km of rivers, and 26 million hectares of water area suitable for aquaculture (OECD/Deniz, 2010) (Table 1). There are a total of 892 fish species in our waters, 512 of which are in our seas and 380 in our inland waters, of which about 100 species are commercially fished (Deniz, 2011).

Table 1. Natural aquatic resources in Türkiye (OECD/Deniz, 2010).

Marine Resources	Coastlines (km)		Surface Area (ha)
Mediterranean, Aegean Sea, Marmara Sea, and Black Sea	7,144		23,475,000
Istanbul and Dardanelles	1,189		1,133,200
Total	8,333		24,607,200
Freshwater Resources	**Number**	**Surface Area (ha)**	**Length (km)**
Natural Lakes	200	900,118	-
Dam Lakes	159	342,377	-
Ponds	750	15,500	-
Rivers	33	-	177,714
Total	1,142	1,261,995	177,714
Grand Total		26.000.000 ha	

Türkiye has an unequal distribution of inland water resources, with an average annual surface runoff of 186 billion m^3 in its 26 river basins. Roughly half of this amount is deemed usable from a technical and economic standpoint. Turkey's share of the world's fishery production is approximately 0.6%. In terms of marine fisheries and aquaculture production, Türkiye is placed at 31^{st} and 30^{th} respectively among 225 countries in 2021 (OECD/Deniz, 2010).

Although the world population is increasing rapidly, land-based resources are decreasing day by day due to the use of agricultural lands for purposes other than their intended purpose, pollution, etc. For this reason, the importance of seafood in meeting the world's food and especially animal protein needs are increasing. Due to illegal, unreported and unregulated (IUU) fishing, pollution, coastal structuring and similar reasons, natural fisheries stocks have been decreasing gradually and have become unable to meet the food needs of human beings.

The importance of aquaculture, which started in China in 1000 BC for the first time in the World (Hishamunda & Subasinghe, 2023) has gradually increased due to the gradual decrease and insufficiency of capture fishery production, and since the middle of this century, commercial aquaculture has been started in many countries of the world, including Türkiye. Although the sector is very new to other sectors, it has developed rapidly and has come to meet half of the world's total aquaculture production.

The world's total fisheries production in 2021 is about 182.1 million tons, of which 90.9 million tons were obtained from aquaculture. Türkiye's total fisheries production in 2021 is 799.9 thousand tons, of which 471.7 thousand tons were obtained from aquaculture. While the share of aquaculture in the world's total fisheries production was 50.1% in the world (2021), it reached 60.6 in Türkiye (2022) (FAO, 2023) (Figure 2, 3).

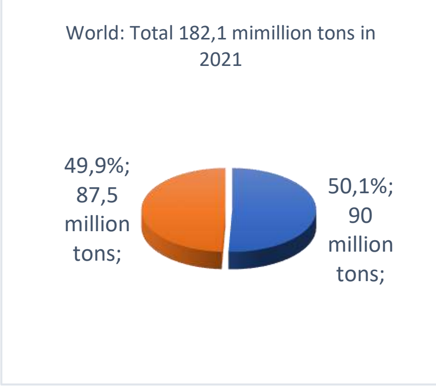

Figure 2. Share of fishery and aquaculture in the the total world's total fisheries production (FAO, 2023).

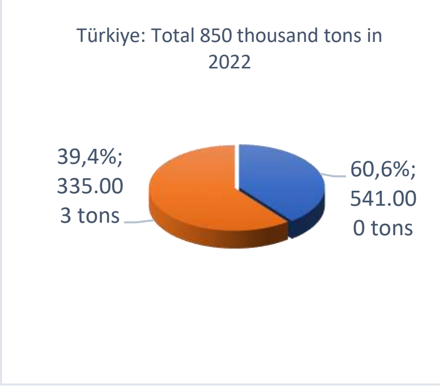

Figure 3. Share of fishery and aquaculture in the Türkiye fisheries production (FAO, 2023).

Europe's total fisheries production in 2021 is 5,036,278 tons, and Türkiye ranks 3rd with 799,844 tons (Figure 4). Total fisheries production in 2022 is 849,808 tons, of which 335,003 tons were obtained from capture fishery and 514,805 tons from aquaculture in Türkiye. The share of aquaculture in total fisheries production is 61% in volume and 86% in value (TURKSTAT, 2023) (Table 2).

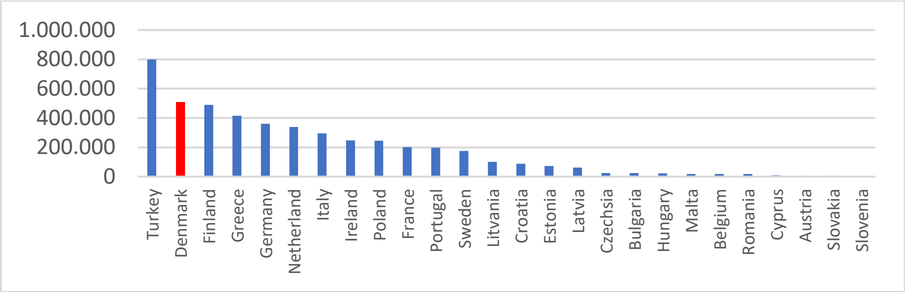

Figure 4. Türkiye's share in total European fisheries production (TURKSTAT, 2023)

Table 2. Fisheries production in tons in Türkiye during in the past five years

Years	Fishery			Aquaculture			Grand Total
	Marine	Inland	Total	Marine	Inland	Total	
2018	283.955	30.139	314.094	209.370	105.167	314.537	628.631
2019	431.572	31.596	463.168	256.930	116.426	373.356	836.524
2020	331.281	33.119	364.400	293.175	128.236	421.411	785.811
2021	295.018	33.140	328.158	335.644	136.042	471.686	799.844
2022	301.747	33.256	335.003	368.742	146.063	514.805	849.808

In the last 20 years in Türkiye, fishery production has been declining gradually due to overfishing, pollution and misuse. Fishery production, which was 508 thousand tons in 2003, decreased to 335 thousand tons in 2022 and will continue to decrease. On the other hand, aquaculture production, which was 80 thousand tons in 2003, reached 515 thousand tons in 2022 and this increase will continue (TURKSTAT, 2023) (Figure 5).

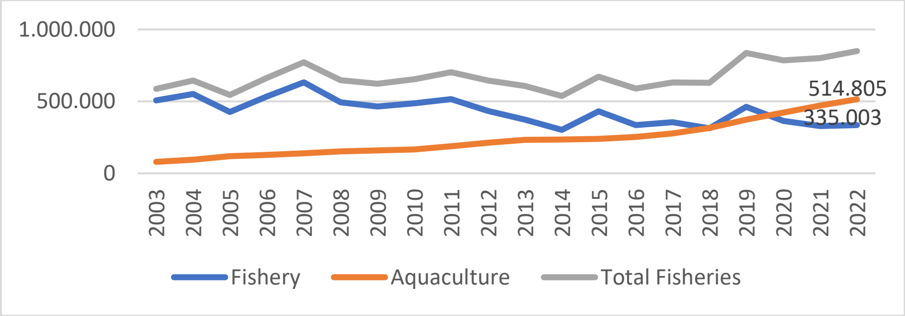

Figure 5. Fisheries production trend in the past decade in Türkiye.

Average per capita seafood consumption; it is 20.05 kg in the world (FAO, 2022) 23.97 kg in EU-28 (EUMOFA, 2022) and 5.09 kg in Türkiye in 2019 (MoAF, 2023). In recent years, per capita seafood consumption in Türkiye has increased and reached 7.3 kg. Of course, this figure is very low compared to the world and EU averages. In order to catch the world average in per capita seafood consumption in Türkiye, it is necessary to consume 3 times more seafood. Between 2009 and 2018, thanks to the increase in aquaculture production, the rate of self-sufficiency in aquaculture increased to 104% (Massa et al., 2020).

General Overview of Aquaculture in Türkiye

Aquaculture is the world's fastest growing food sector, with huge potential for expansion. It plays a critical role in global food production and over half the aquatic foods for human consumption are farmed. FAO's work in aquaculture stems from Blue Transformation, a vision committed to building sustainability and resilience, minimizing environmental impacts, improving biosecurity and disease control with the support of technology and innovation, and developing capacities to ensure equitable outcomes that further develops the human, social, cultural and economic dimensions of aquaculture.

In recent years, aquaculture has experienced remarkable growth. As the demand for fish rises and many capture fisheries reach their maximum potential, its significance will only continue to grow in the future. Currently, more than half of the fish consumed by humans comes from aquaculture, and this industry is predicted to meet the growing global demand for aquatic food, which is projected to rise by 2% annually in the next few decades.

This study utilizes a variety of tools, including the Ecosystem Approach to Aquaculture and technical guidelines for spatial planning, responsible health management, genetic resource management, aquaculture governance, and aquaculture certification. Contribute to the effort of ensuring that aquaculture produce reaching consumers follow the guidelines of the Code of Conduct.

The economic and environmental impact of aquaculture production has been positively influenced by the increasing focus on researching the connections between fish diets, nutrition, growth, and health. Through the implementation of new ingredients and technological advancements, fish oil and fishmeal can be replaced in commercial feed while maintaining the nutritional value of aquaculture products (FAO, 2018).

Türkiye, it is in an ideal location for aquaculture due to its 8,883 km coastline, being surrounded by seas with different characters on three sides, lagoons and having many dams, dam lakes, manmade lakes, ponds and streams. Through the use of various production systems, a wide range of aquatic species can be successfully farmed in fresh, brackish, or salt water (Okumus & Deniz, 2007; Yıldız et al., 2024).

Aquaculture in Türkiye is a relatively young sector compared to other sectors. Fish farming in Türkiye is started with carp in 1960's and rainbow trout culture fallowed it in the early 1970s. Sea bass and sea bream farming started in 1985 in the Aegean Sea. After than it has developed rapidly thanks to its huge potential, the state's support of the sector, the rapid adaptation of producers to developing and changing technologies, and their technical capacity, reaching 2,382 farms in 2022, and the total capacity reached 784,864 tons (MoAF, 2023) (Table 3).

Table 3. Number and capacity of fish farms in Türkiye (MoAF, 2023).

Sub-sector	Number of farms	Total capacity (tons / year
Inland aquaculture	1.735	259.000
Marine aquaculture	533	525.812
Total	2.382	784.864

Commercial aquaculture started in the 1990s with the widespread production of sea bream, sea bass and trout. Later, in the 2000s, new species such as blue fin tuna, turbot, shrimp, and mussel began to be grown. Finally, thanks to the contribution of Turkish salmon, which has been started to be grown in the Black Sea since 2020 and whose production is increasing rapidly, it has gained a very successful momentum (Table 4). Turkish aquaculture, which started with 3.075 tons in 1986, has grown by 15.000% until 2022 and reached 514.805 tons (MoAF, 2023) (Figure 6).

Table 4. Number and capacity of fish farms in Türkiye (MoAF, 2023)

Year	Marine Aquaculture	% of total production	Inland Aquaculture	% of total production	Total
2013	2013	110.375	47,3	123.018	233.393
2014	2014	126.894	54,0	108.239	235.133
2015	2015	138.879	57,8	101.455	240.334
2016	2016	151.794	59,9	101.601	253.395
2017	2017	172.492	62,4	104.010	276.502
2018	2018	209.370	66,6	105.167	314.537
2019	2019	256.930	68,8	116.426	373.356
2020	2020	293.175	69,6	128.236	421.411
2021	2021	335.644	71,2	136.042	471.686
2022	2022	368.742	71,6	146.063	514.805

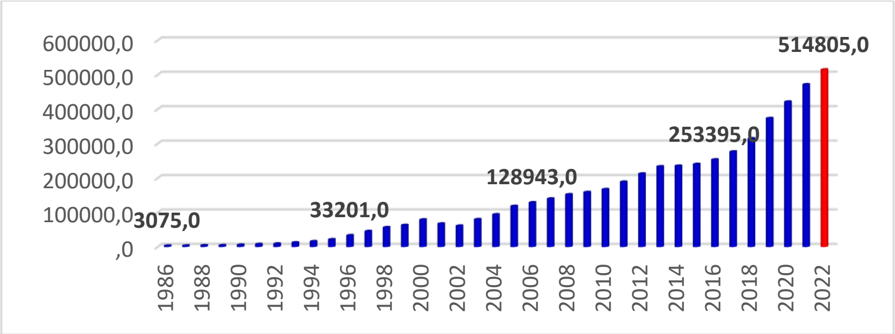

Figure 6. Growing trend of Turkish aquaculture in 1986-2022 (MoAF, 2023).

Aquaculture Policy, Administration and Legislation

The Ministry of Agriculture and Forestry (MoAF) is the main authority on fisheries and aquaculture. All subjects such as fisheries and aquaculture management, monitoring, protection, incentives and technical assistance are carried out by the General Directorate (DG) of Fisheries and Aquaculture.

Aquaculture practices rely on the Fisheries Law, No.1380 of 1971, which codifies definitions and serves as the basis for related regulations. According to Fisheries Law, individuals seeking to commercially farm aquatic species must submit an application to the MAF, disclosing the location, features, and operation plans of their facilities. The MAF grants permission if there are no negative consequences for public health, the national economy, navigation, or science and technology (Gözgözoğlu, 2007).

The Aquaculture Regulation, issued in 2004, establishes the procedures and principles governing aquaculture as outlined in the Fisheries Law. The addition of fish welfare was incorporated into this regulation through amendments in 2007 and 2009 (Atalay & Maltaş, 2020).

This regulation covers and sets out rules for the following issues:

- Site selection for inland and marine farms
- Application and evaluation procedures for fish farming licenses
- Approving the projects and issuing licenses
- Improving production capacity, species etc., cancellation, site changes and sales
- Other aquaculture activities (tuna fattening, organic farming, etc.)
- Importing brood fish, egg and fry
- Compulsory technical staff employment
- Fish health management
- Environmental impacts and protection

- Monitoring and control of farming activities
- Fish welfare

Technical details regarding the establishment of fish farms and the determination of the conditions related to production are carried out by MAF, and many institutions such as the Ministries of Environment, Transport, Tourism, and their legislation are involved in this process.

The effects of aquaculture on the environment in Turkey are a source of ongoing debate. The legal and technical framework for this subject encompasses not only Fisheries and Aquaculture Regulations, but also Water Quality Regulation and Environmental Impact Assessment (EIA) Regulation. Environmental Impact Assessment (EIA) Reports are an essential requirement during the construction phase, involving in-depth study and analysis to provide a comprehensive evaluation of the potential environmental risks and necessary precautionary measures.

As mentioned above, according to the Fisheries Law, MAF is responsible for all aquaculture activities. However, due to the fact that fish farming is a multidisciplinary activity and new legislation related to other stakeholders has been put into practice, many institutions and organizations listed below are involved in aquaculture activities:

- Presidency (Department of Strategy and Budget)
- Ministry of Agriculture and Forestry (MoAF): DG of Fisheries and Aquaculture, DG of Food and Control, DG of Agricultural Research and Policies
- Ministry of Environment, Urbanization and Climate Change (MEUCC): DG of Environmental Management, DG of EIA, Permission and Inspection, DG of Spatial Planning
- Ministry of Treasury and Finance (MTF): DG of Foreign Economic Relations, Department of Revenue Management
- Turkish Statistical Institute (TURKSTAT)

- Ministry of Interior Affairs (Coastguard and Gendarmerie)
- Ministry of Health (MH): Institute of Public Health dealing with hygiene and the sanitary of fish and fish products
- Ministry of Labor and Social Security (MLSC)
- Ministry of Transport and Infrastructure (MTI): DG of Shipyards and Coastal Structures
- Municipalities: Quality control and conservation in the local open markets
- Ziraat Bank: Credits

The aquaculture activities are carried out while taking into account the laws and regulations of these institutions. Main laws and regulations related to aquaculture and seafood are:

- Fisheries Law
- Environment Law
- Continental Water Law
- Cooperatives Law
- Animal Health and Sanitation Law
- Producer Unions Law
- Aquaculture Regulation
- Environmental Impact Assessment Regulation
- Regulations Governing the Control of Water Pollution
- Regulation of Environmental Management of Marine Fish Farms

Recently, the Turkish government has developed a National Marine Aquaculture Development Plan to minimize conflicts and provide stable ground for the future growth of the aquaculture sector. To prevent impacts of the fish farms some measures were introduced with other stakeholders.

Below are the criterias used for allocation of mariculture zone by MoAF and Ministry of Environment, Urbanization and Climate Change:

- *Criterias for Suitability and possibility of mariculture*
  - ✓ Water quality
  - ✓ Psychical and chemical conditions
  - ✓ Site selection criteria
  - ✓ Water depth ≤ 30m
  - ✓ Distance from coastline ≤0.6 mile
  - ✓ Current speed ≤ 0.1 m/sec
- *Criterias for Protection status*
  - ✓ Special protected areas
  - ✓ Sites of archeological and historical
  - ✓ Wildlife protected areas, etc.
  - ✓ Other coastal uses
  - ✓ Tourism, urbanization, marine transportation, fishing, recreation, etc.

For the aquaculture sector, the main problems relate to the lack of consideration of aquaculture in spatial planning and management of integrated coastal areas, leading to poor implementation of the strategy for the allocation of priority areas for Aquaculture (AZA). The lack of criteria and indicators for the allocation of areas in the sea, to be applied on the territory according to local specificities would enable a more participatory selection process for aquaculture sites. This would in effect ease tension after the sites are built.

Aquaculture Production Trend in Türkiye

Aquaculture, which includes fish, shellfish, and the production of aquatic plants, is the world's fastest growing sector in the food industry. Nowadays, fisheries and aquaculture provide a significant part of the daily animal protein requirements in many developing countries. Food and protein demands are expected to increase if the world population reaches 9.6 billion until 2050.

Fisheries and aquaculture play crucial roles in providing food, nutrition, income, and livelihoods for millions of people worldwide, as aquaculture now accounts for more than half of the world's fish supply for human consumption. Furthermore, when it is considered that aquaculture supplies 49% of fish to global markets, the activation of this sector will provide food security for the poorest people in the world and also will provide added value in social and economic terms.

Aquaculture is the fastest growing food production sector in Türkiye in the past 10 years. It is known to be one of its activities and this is definitely a valid trend in Türkiye as well. Aquaculture in Türkiye has grown significantly in the last 20 years in line with the increase in domestic and international consumers' demand for fresh and quality fish.

Aquaculture in Türkiye started with trout in the inland waters in the 1970s and sea bream in 1985, but due to inexperience and the inability to follow the technological developments sufficiently, it has fallen behind a bit compared to the countries that have started aquaculture before. However, following the start of academic education on aquaculture in the 1980s and the execution of projects aimed at the needs of the sector in cooperation with the private sector and universities, significant developments in aquaculture in Turkey have been achieved in a short time (Okumuş & Deniz, 2007).

Turkish aquaculture showed continuous increase between the years 1986-2016, except for the years 2001-2002. Aquaculture production, which was 79.000 tons in 2000, has increased regularly until today and reached 514.805 tons in 2022 with an increase of 551% (MoAF, 2023). Looking at the trend of marine aquaculture and freshwater aquaculture production in the last 10 years in Türkiye, it is seen that while the production amounts were equal in 2010, marine aquaculture increased by 3,3 times and reached 335,6440 tons in 2022, and freshwater aquaculture reached 136,042 tons with an increase of 1,2 times (Figure 7). In other words, marine aquaculture has increased twice as much as freshwater aquaculture (Table 5) (TURKSTAT, 2023).

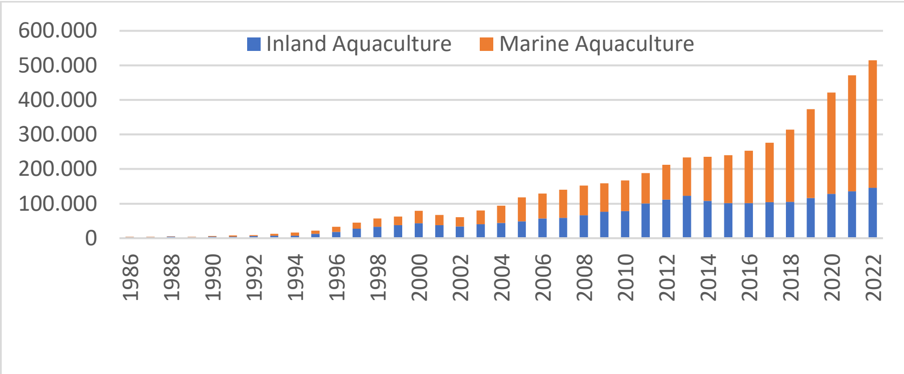

Figure 7. Development trend of Turkish aquaculture in 1986-2022 (TURKSTAT, 2023).

Table 5. Marine and inland aquaculture productions in the past decade in Turkey (tons) (TURKSTAT, 2023)

Year	Marine	% in total	Inland	% in total	Total
2013	110.375	47,3	123.018	52,7	233.393
2014	126.894	54,0	108.239	46,0	235.133
2015	138.879	57,8	101.455	42,2	240.334
2016	151.794	59,9	101.601	40,1	253.395
2017	172.492	62,4	104.010	37,6	276.502
2018	209.370	66,6	105.167	33,4	314.537
2019	256.930	68,8	116.426	31,2	373.356
2020	293.175	69,6	128.236	30,4	421.411
2021	335.644	71,2	136.042	28,8	471.686
2022	368.742	71,6	146.063	28,4	514.805

In Türkiye, a total of 42 million ₺ income was obtained from aquaculture in 2022, 81% of which was obtained from marine aquaculture and 19% from freshwater aquaculture (TURKSTAT, 2023) (Table 6). Aegean

Region takes the first place in aquaculture by far in Türkiye. The provinces of Aegean region with the largest share in aquaculture production in 2022 are respectively; Muğla (170.206 tons, 33%), Izmir (111.229 tons, 21,6%) and Elazığ (31.176, 17%) (MoAF, 2023).

Table 6. Marine and inland aquaculture production values in the past decade in Türkiye (million ₺) (TURKSTAT, 2023)

Year	Marine	% in total	Inland Water	% in total	Total
2013	1.129	66,2	576	33,8	1.704
2014	1.523	70,5	637	29,5	2.160
2015	1.874	73,0	695	27,0	2.569
2016	2.464	76,1	775	23,9	3.239
2017	3.163	78,1	887	21,9	4.049
2018	4.379	78,1	1.228	21,9	5.607
2019	5.890	76,5	1.804	23,5	7.694
2020	8.586	79,1	2.273	20,9	10.859
2021	15.179	82,1	3.303	17,9	18.482
2022	34.133	81,2	7.915	18,8	42.048

Structure of Aquaculture Sector in Türkiye

Aquaculture is carried out in inland waters, in dam lakes, natural lakes, streams and other water resources and in the seas. Concrete raceways, floating cages, and ponds are the three main production systems utilized in Türkiye for fish cultivation. Raceways are primarily employed for trout farming, whereas floating cages are utilized to cultivate sea bass, sea bream, trout, and tuna. Both concrete circular ponds and fiberglass tanks play a role in trout production, but the latter is typically preferred for hatcheries and juvenile production. As of now, the RAS system is only used in hatcheries. However, the use of the RAS system will gradually increase in the coming years as a result of the gradual decrease in water resources and the increase in demand. It supports the government financially those who use the RAS system. Mussels are cultured on ropes suspended from floating rafts.

The cages utilized are predominantly circular in shape and constructed from High Density Polyethylene (HDPE), with ø sizes varying between 20 to 100 meters. The size of cages used in sea bass and sea bream farms range from 30-50 meters, while those used in trout production are smaller, measuring less than 20-30 meters. Tuna farmers, however, prefer cages of over 50-100 meters. Offshore production of sea bass and sea bream has seen a surge in popularity among major companies, leading to the establishment of standardized systems. These systems have the capability to produce 2,000 metric tons per year and consist of 18 cages measuring ø50 m, along with automated feeding systems.

Although the amount of aquaculture production in inland waters was higher than that in the seas until 2013, the amount of production in the seas for the last 8 years has been higher than the amount of production from inland waters. Production from marine aquaculture totaled 368.742 tons (71,6%) whilst freshwater aquaculture produced 146,03 tons (28,4%) in 2022 (TURKSTAT, 2023).

Fish farming in freshwater is conducted through land-based facilities that draw water from rivers (the most common type of production unit), or through cages placed in lakes and dams. (Figure 8). Currently, trout farming is carried out in concrete ponds 25-30 m long, 2.5-4 m wide and 0.7-1.5 m deep in inland waters and in polyethylene net cages with a diameter of 20-30 m in dam lakes. As of 2022, there are 1829 fish farms with a total capacity of 259,052 tons / year operating in freshwater resources (MoAF, 2023).

Figure 8. Trout farm in Mugla, Aegean Region in Türkiye

Most of the sea farming production is in the offshore cages in the Aegean, Mediterranean and Black Sea coasts, at a minimum distance of 0.6 nautical miles from the coast, at a depth of at least 30 m and with a current speed of 0.1 m/sec, and established in the sea areas determined by the agreement of all stakeholders and decision makers (MoEUCC, 2020). Avşar region of Muğla's Milas district, there are many farms that cultivate sea bream, sea bass, shrimp and turbot in earthen ponds using the brackish water coming out of the ground (Figure 9).

Figure 9. Sea bass and sea bream farm in Muğla, Aegean Region.

As of 2022, there are 533 marine fish farms with a total capacity of 525,812 tons / year. Out of a total of 533 sea fish farms, 108 of them operate in soil ponds on land, and the remaining 425 fish farms operate in the seas. There are 2,382 freshwater fish farms in Türkiye with a total capacity of 784,864 tons, including inland water and sea. In the production of sea bream and sea bass, and therefore in the production of marine fish, in the top three, respectively; Muğla, İzmir and Aydın are located. In trout production and therefore inland aquaculture, respectively; Elazig, Muğla and Burdur are at the top (MoAF, 2023) (Table 7).

Table 7. Key provinces in aquaculture production in terms of production area and species (MoAF, 2023)

	Categorisation	Province	Production (tons)	Share (%)
Production	**Total Production**			
	1.	Muğla	170.206	33,1
	2.	İzmir	99.640	21,6
	3.	Aydın	31.106	6,0
	Marine			
	1.	Muğla	143.693	39,0
	2.	İzmir	111.069	30,1
	3.	Mersin	27.792	7,5
	Freshwater			
	1.	Elazığ	31.106	21,3
	2.	Muğla	26.513	18,2
	3.	Şanlıurfa	7.161	4,9
Species	**Trout (Freshwater+Marine)**			
	1.	Elazığ	31.106	16,3
	2.	Muğla	26.500	13,9
	3.	Samsun	18.405	9,6
	Sea bream			
	1.	Muğla	66.750	43,8
	2.	İzmir	52.231	34,3
	3.	Mersin	25.112	16,5
	Sea bass			
	1.	Muğla	72.887	46,5
	2.	İzmir	52.185	33,3
	3.	Aydın	21.033	13,4

The important provinces where aquaculture is carried out intensively in the seas and inland waters and their shares in the total aquaculture production are given in Figure 10 and Figure 11 below (TEBGE, 2023). Looking at the distribution of aquaculture production by regions, it is seen that the Aegean Region takes the first place with 61%, the Black Sea Region takes the second place with 13%, and the Mediterranean Region takes the third place with 11% (MoAF, 2023) (Figure 12).

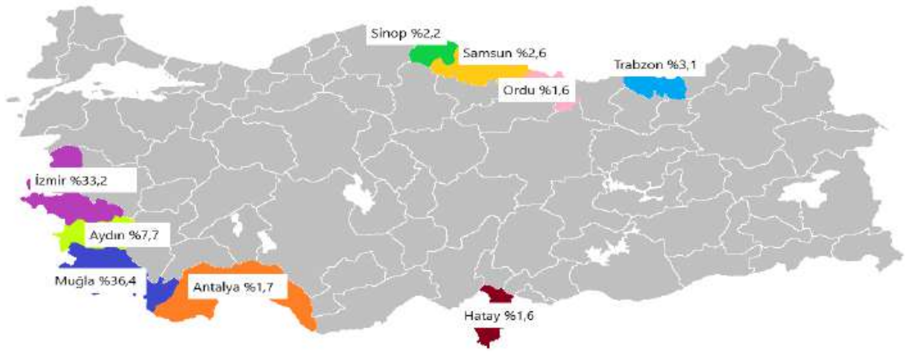

Figure 10. Important provinces where marine aquaculture is carried out and their share in total production (TEBGE, 2023).

Figure 11. Impant provinces where inland aquaculture is carried out and their share in total production (TEBGE, 2023).

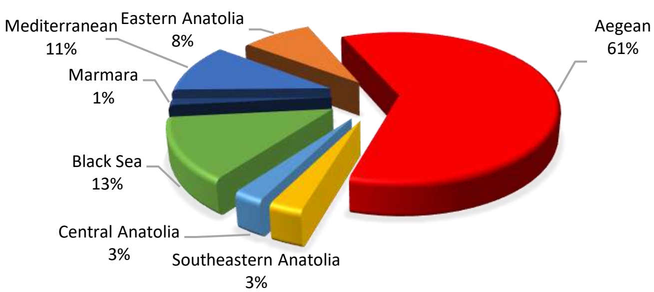

Figure 12. Aquaculture production amount and share by regions (MoAF, 2023).

In this regard, most of the marine aquaculture production in Türkiye (88%) is obtained from the farms operating in the Aegean, as the geographical and hydrographic conditions are very suitable for the species being grown. The number of marine fish farming facilities operating on the Mediterranean and Black Sea coasts is lower than in the Aegean. Production is mostly carried out in Mersin in the Mediterranean, and there are a limited number of facilities in other provinces. 64% of the total marine fish farms on the Aegean coasts are located in Muğla, 23% in İzmir and 13% in Aydın.

Currently the following species are cultured commercially: European sea bass (*Dicentrarchus labrax*), gilthead sea bream (*Sparus aurata*), rainbow trout (*Oncorhynchus mykiss*), blue-fin tuna (*Thunnus thynnus*), brown meagre (*Sciaena umbra*), shi drum (*Umbrina cirrosa*), pink dentex (*Dentex gibbosus*), carp (*Cyprinus carpio*), European catfish (*Silurus glanis*), and Mediterranean mussel (*Mytilus galloprovinciialis*) (MoAF, 2023) (Table 8).

Table 8. Aquaculture production in terms of production area and species in 2022 (MoAF, 2023)

Production area / Species	Production (tons)
Inland water	146.063
Trout (Rainbow trout)	144.347
Trout (Salmo sp.)	1.302
Carp	293
European catfish	95
Frog	25
Sea water	368.742
Turkish salmon (Rainbow trout)	45.454
Sea bream	152.469
Sea bass	156.602
Shi drum	18
Meagre	4.771
Pink dentex	3
Bluefin tuna	3.879
Mussel	5.469
Total	514.805

In the Mediterranean, experimental or pilot scale cultivation has brought about the cultivation of major new or alternative species like common dentex (*Dentex dentex*), common sea-bream (*Pagrus pagrus*), sharp snout sea-bream (*Puntazzo puntazzo*), white grouper (*Epinephelus aeneus*), striped sea bream (*Lithognathus mormmyrus*), greater amberjack (*Seriola dumerili*), white sea-bream (*Diplodus sargus*), two-banded sea-bream (*Diplodus vulgaris*) and Black Sea turbot (*Psetta maxima*) (Deniz, 2011).

While sea trout and sea bass were produced in the Black Sea in previous years, with the increasing demand for Turkish salmon in recent years, most of the facilities are currently farming salmon. The province of Muğla ranks first (170.206 tons) in the production of aquaculture species being the first producer of trout (26.513 tons), sea bass and sea bream (143.693 tons). After Muğla, Izmir is the second largest province in terms of production with 95.772 tons. These two provinces represent the 60 percent of the total aquaculture production in Türkiye.

As of 2022, there are 28 marine hatcheries with a total capacity of 1.087.500.000 juveniles/year and 88 detached freshwater fish hatcheries with a total capacity of 625.050.000 juveniles/year in Türkiye. In addition, most of the trout farms operating in inland waters produce their own juveniles in their own production facilities, and the total juvenile's production capacity in these farms is 4.268.819.271 juvenile/year.

Foreign Trade of Fisheries and Aquaculture in Türkiye

The foreign trade of fisheries products continues to be a strong sector for Turkey as it maintains its position as a net exporter. Türkiye's aquaculture exports have seen a significant boost due to the recent progress in aquaculture production and processing technologies. According to the export-import data, there is a significant discrepancy between exports and imports in 2022, with exports surpassing imports by 136,000 tons and 339 billion dollars in value (MoAF, 2023) (Table 9).

Table 9. Fisheries and aquaculture trade in Türkiye in 2022 (MoAF, 2023)

Year	Export		Import	
	Volume (tons)	Value (million $)	Volume (tons)	Value (million $)
2003	29.937	125	45.606	33
2004	32.804	181	57.694	54
2005	37.655	206	47.676	69
2006	41.973	233	53.563	83
2007	47.214	273	58.022	97
2008	54.526	383	63.222	120
2009	54.354	318	72.686	106
2010	55.109	313	80.726	134
2011	66.738	395	65.698	174
2012	74.006	414	65.384	176
2013	101.063	568	67.530	188
2014	115.381	676	77.551	198
2015	121.053	692	110.761	251
2016	145.469	790	82.074	181
2017	156.681	855	100.444	230
2018	177.500	951	98.315	189
2019	200.226	1.026	90.684	189
2020	201.375	1.065	85.269	157
2021	238.732	1.376	104.708	217
2022	251.416	1.651	115.189	313

According to TURKSTAT (2023) data, Türkiye's aquaculture trade showed the highest increase in 2022 compared to the previous year, with an increase of 24% in exports and 30% in imports. 1 billion 651 million dollars of aquaculture exports realized in 202 were made to 106 countries and 75% of these countries are European Union countries (Figure 13, Figure 14). While the largest expenditure in total aquaculture imports is made to Norway, the imported products are mostly mackerel/snails and salmon. Mackerel and sardines are imported from Morocco, where the highest number of imports (36%) is realized.

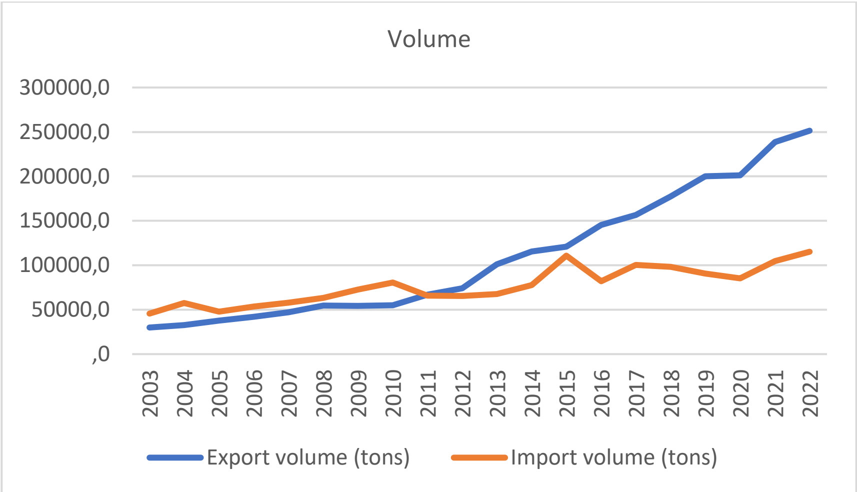

Figure 13. Trade trend of Turkish seafoods in 2022 as volume (MoAF, 2023).

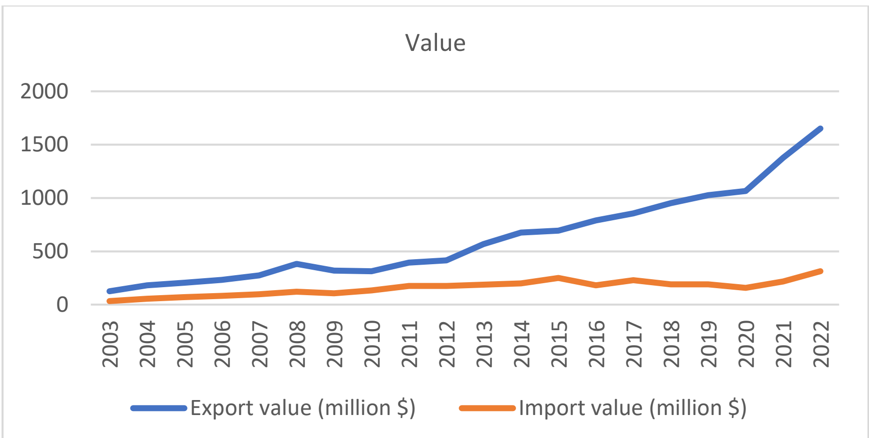

Figure 14. Trade of trend of Turkish seafoods in 2003-2022 as value (MoAF, 2023).

The most important fish exported from Türkiye are trout, Turkish salmon, sea bream, sea bass and tuna (MoAF, 2023) (Table 10,11,12,13,14,15). In 2022, Türkiye exported farmed fishes to 106 countries around the world. Export amount was recorded as 251.416 tons with an increase of 5,3% compared to the previous year. When the last year's data on fisheries exports are analyzed, an increase has been recorded since 2014.

Table 10. Export volume and values of important cultured fishes in 2021-2022 (MoAF, 2023)

Species	2021		2022	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (1000 $)
Trout	27.718	142.727	25.717	139.008
Turkish salmon	22.851	130.896	43.663	312.232
Sea bream	71.325	303.539	61.267	279.299
Sea bass	48.643	263.636	44.393	270.148
Blue fin tuna	5.211	60.851	4.556	68.006
Total	175.748	901.645	179.595	1.069

Table 11. Trout export-import volume and values in the past decade (MoAF, 2023)

Years	Export		Import	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (10000 $)
2013	20.277	102.488	177	1.283
2014	21.192	110.160	180	1.141
2015	19.195	89.026	510	2.336
2016	22.014	103.082	1.678	10.766
2017	23.648	107.777	197	1.313
2018	25.343	130.689	415	2.961
2019	27.381	145.599	937	5.861
2020	23.597	119.990	118	531
2021	27.718	142.727	124	797
2022	25.717	139.008	97	667

Table 12. Export-Import volumes and values of Turkish salmon in 2020-2022 (MoAF, 2023)

Years	Export		Import	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (10000 $)
2020	12.418	56.808	438	2.769
2021	22.851	130.896	162	1.041
2022	43.663	312.232	479	4.205

Table 13. Sea bream export-import volumes and values in the past decade (MoAF, 2023)

Years	Export		Import	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (10000 $)
2013	22.069	104.128	52	560
2014	27.515	153.706	58	789
2015	31.739	166.104	69	758
2016	43.808	191.871	93	781
2017	46.456	206.310	294	1.277
2018	52.532	218.759	113	976
2019	60.677	239.120	55	214
2020	63.004	260.079	10	52
2021	71.325	303.536	92	472
2022	61.267	279.299	19	99

Table 14. Sea bass export-import volumes and values in the past decade (MoAF, 2023)

Years	Export		Import	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (10000 $)
2013	18.157	98.879	68	597
2014	22.871	137.775	43	516
2015	26.199	145.793	24	422
2016	27.223	152.153	24	640
2017	32.792	172.004	24	110
2018	42.584	195.398	207	1.022
2019	49.336	195.473	24	91
2020	45.434	207.741	5	33
2021	48.643	263.636	31	199
2022	44.393	270.148	76	350

Table 15. Blue fin tuna export-import volumes and values in the past decade (MoAF 2023)

Years	Export		Import	
	Volume (tons)	Value (1000 $)	Volume (tons)	Value (10000 $)
2010	2.297	40.836	202	1.154
2011	1.950	39.923	325	3.324
2012	1.777	40.679	348	5.950
2013	2.035	39.075	564	9.435
2014	2.086	36.986	772	13.268
2015	2.652	44.442	1.220	18.303
2016	2.978	42.220	617	6.489
2017	4.071	56.919	876	11.642
2018	4.122	58.192	465	6.248
2019	6.435	79.192	874	9.822
2020	6.635	71.824	350	3.162
2021	5.211	60.851	447	4.780
2022	4.556	68.006	1.092	18.168

Covid-19, which affected the whole world in 2020, narrowed the export of fisheries around the World. As in 2022 global fisheries trade, there has been an increase in Türkiye. In 2022, the highest export was to Russia with 18%, while 64% of the export amount was made to European countries.

Conclusion

Aquaculture, which is very new compared to other sectors, started in the 1970s in Türkiye and has achieved an extraordinary development thanks to the availability of suitable water resources, the State's continuous support to farmers in financial, legal and technical matters, and the rapid adaptation of farmers to changing and developing technological developments. The main species commercially grown in Türkiye are trout, sea bream, sea bass, blue fin tuna and Turkish salmon, followed by meagre, shi drum, pink dentex, carp, European catfish, sturgeon, turbot and Mediterranean mussel (Bozkurt, 2011; Yıldız et al., 2024).

As of 2022, Türkiye's total fisheries production is 849,808 tons, of which 514,805 tons were obtained through aquaculture. Aquaculture production, which was only 3,000 tons in 1986, increased by 15,000 % until 2022 and had a share of 61% in amount and 86% in value in total fisheries production (TURKSTAT, 2023). Aquaculture has become the fastest growing sector in Türkiye with its 551% growth performance in the last 20 years. Sea farming, which has increased by 700% in the last 20 years, has an important share in the blue growth and blue economy in Türkiye due to its 8,833 km coastal length surrounded by seas on three sides.

Turkish aquaculture products are exported to 106 countries around the world as of 2022. The largest market is EU countries, with the Russian Federation, USA and China growing markets. The recorded developments have firmly established Türkiye as the foremost country in terms of utilizing living marine resources for the blue economy, surpassing all other European countries and dominating in the Mediterranean basin. Currently, Türkiye holds the title of being the biggest fish producer in the Mediterranean Basin and the second biggest in Europe, following closely behind Norway. At present, Turkey holds a 30% stake in the European market for sea bream and sea bass. The country is also the top producer of trout in Europe and leads the world in the production of sea bass and sea bream.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Fiction: HD, YB; Literature: HD; Manuscript writing: YB; Supervision: YB. All authors approved the final draft.

Ethical Statements

Local Ethics Committee Approval was not obtained because experimental animals were not used in this study.

Data Availability Statement

Data supporting the findings of the present study are available from the corresponding author upon reasonable request.

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