AQUACULTURE SUSTAINABILITY:

Feeding Strategies, Environmental Impact, and Solutions

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PREFACE

Aquaculture plays an increasingly critical role in global food security, economic development, and sustainability of ecosystems. However, its rapid expansion also poses significant challenges, including environmental pressures, resource inefficiencies, and socio-cultural complexities. In this context, sustainable aquaculture practices aim to enhance production efficiency while minimizing environmental and societal impacts.

This book, *Aquaculture Sustainability: Feeding Strategies, Environmental Impact, and Solutions*, provides a comprehensive overview of the knowledge and practices necessary to promote sustainability in aquaculture. Comprising 11 chapters, this work addresses diverse aspects of the sector and bridges theoretical foundations with practical applications, serving as a valuable resource for researchers, industry professionals, and policymakers.

Each chapter is designed to deepen understanding, foster innovative approaches, and offer practical solutions that balance ecological, economic, and social considerations. We extend our gratitude to all contributing authors and the Global Academy Publishing team for their efforts, and hope this work serves as a meaningful contribution to both the science and practice of sustainable aquaculture.

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CHAPTER I

INTRODUCTION TO SUSTAINABLE AQUACULTURE PRACTICES

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Introduction

Aquaculture, which is the culture of aquatic flora and fauna, has emerged as one of the most vibrant in the provision of marine foods around the world. Although aquaculture was introduced in the Pacific Island Countries and Territories (PICTs) in the 1950s and 1960s, it was not until a few decades ago that this sector began to grow, expand, and play a significant role in livelihoods and food security (Charlton et al., 2016). The global aquaculture industry has experienced considerable growth over the last 20 years, successfully meeting key objectives of environmental, economic, and societal sustainability (Boyd et al., 2020). The global production of aquaculture expanded six times between 1990 and 2020, making aquaculture the fastest-growing food production sector. In 2020 alone, 122.6M tonnes (live weight) were produced in freshwater, brackish and marine systems. About 424 aquatic species are currently being farmed to enable many millions of people to receive nourishment, employment and alleviate poverty. Aquaculture is directly related to the United Nations Sustainable Development Goals (SDGs). The industry is relevant to SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water) (Troell et al., 2023). Aquatic foods are important sources of nutrition, food security, and economic sustainability in most countries whose coastlines and freshwater resources (either captured or cultured) are essential contributors to their food income (FAO, 2022). The industry currently consists of inland freshwater (62% and 75% live-weight and edible weight, respectively), which has dominated the sector globally in terms of production (Naylor et al., 2021; FAO, 2022). Due to this, aquaculture has been essential in meeting the increasing demand for protein, sustaining livelihoods, and enhancing resilience to malnutrition and poverty.

Sustainability is another issue that the further development of aquaculture has attracted. In the modern age, the issue of aquaculture production being environmentally responsible and socially acceptable is no longer a point of debate (Engle & D'Abramo, 2016). Sustainability has evolved from an abstract idea into the main structure on which aquaculture management and regulation are built in recent years. This includes enhancing the performance of farmed specimens, supporting stocking ratios to guarantee animal comfort and addressing environmental problems, including water pollution, disease propagation, excessive medicine use, rarely used feed and waste (da Silva et al., 2013). Sustainable aquaculture possesses ecological integrity, social acceptability, economic feasibility and technological efficiency. Sustainability in aquaculture is an immediate need, as the latest advances highlight three primary themes. For starters, environmental strain is increasing due to the worldwide trend toward more intensive aquaculture systems. Despite the circularity provided by nutrient recycling, substantial aquaculture produces changes in land use because of the massive areas that it often involves. Waste, feed and disease management in intensive production increase yields at the cost of the environment (da Silva et al., 2013). Second, the composition of aquaculture feed is changing. The sector is gradually replacing aquatic-based protein with crop-based alternatives in the diets of carnivorous fish. Although this reduces reliance on marine fish stocks, it transfers environmental pressure to terrestrial ecosystems, including soil degradation, deforestation, and freshwater depletion. Additionally, crop-based feed contributes to eutrophication in freshwater systems (Pahlow et al., 2015). Third, aquaculture increasingly depends on freshwater ecosystems. Freshwater aquaculture already provides the majority of edible output, yet competition for water resources is rising due to agriculture, urbanisation, and energy demands. Protecting and regenerating the quality of freshwater ecosystems has therefore become a priority for the sector (Naylor et al., 2021; FAO, 2022).

These three trends underscore the need to develop production systems that minimise pressure on freshwater and terrestrial resources. Recirculating aquaculture systems (RAS) and biofloc technologies offer ways to reduce water consumption. In contrast, marine-based systems such as seaweed and mussel farming can shift production away from overused freshwater sources. Furthermore, transitioning to aquafeeds derived from non-food-competing ingredients, within circular economy frameworks, may lower indirect land-use impacts and support resource efficiency (Chary et al., 2024). For aquaculture to be considered sustainable, it must have a neutral or ideally positive impact on the environment, maintain economic viability, and achieve social acceptability. Environmental sustainability requires reducing effluents, preserving biodiversity, and responsibly managing water resources. Economic sustainability ensures profitability and resilience, while social sustainability depends on community acceptance, fair employment, and consumer trust. Numerous worldwide scientific studies suggest that reputational and market risks are inherent to aquaculture companies whenever public perceptions of the practice are negative. However well the economy and technology are performing, negative public opinion can curtail investment, reduce demand, and disrupt growth. Hence, sustainability calls for balancing social legitimacy with ecological performance and financial rewards. Improved management for productivity, yield gaps, and profits is crucial if aquaculture is to alleviate poverty and ensure a stable food supply, especially in rural areas. To achieve these objectives, aquaculture must progress in tandem with other forms of economic and social development. Along with food variety, aquaculture contributes to job creation and income generation in rural economies, which in turn support development objectives.

The Need for Sustainability in Aquaculture

The rapid expansion of aquaculture has made it a crucial source of seafood worldwide. Meanwhile, the sector's rapid expansion has raised questions regarding its long-term environmental and social impacts (Alghamdi & Haraz, 2025). Sustainability has thus been placed at the center of the advancement of aquaculture to balance ecological responsibility, financial viability, and social acceptance. Without integrating sustainability at the heart, aquaculture might be undermining the resources and cultures it relies upon.

Principles of Sustainable Aquaculture Practices

Sustainable aquaculture is crucial to satisfy global demand for seafood while protecting local communities and the environment. It comprises a set of guiding principles to ensure that aquaculture activities are socially, economically, and ecologically sound (Fig. 1). These concepts underpin long-term sustainability in aquatic food production methods. Their understanding and application are crucial to balance conservation and productivity.

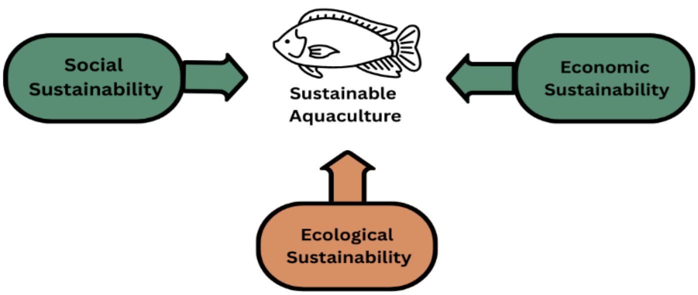

Figure 1. Guiding principles of Sustainable Aquaculture (Created by author, 2025)

Environmental Responsibility

The ecological impact must be decreased for sustainable aquaculture. In case farming operations aren't controlled, they can increase drinking water contamination, habitat destruction and also biodiversity loss. Actions to safeguard delicate ecosystems, such as wetlands and mangroves, reducing chemical usage and enhancing waste management are necessary. Site selection is particularly crucial to avoid aquaculture development harming delicate ecosystems. An ecosystem-based management approach to aquaculture based on the

Code of Conduct for Responsible Fisheries was emphasized by FAO. Human flourishing, environmental preservation, and effective local, international, and national leadership form the foundational assumptions of this paradigm (Soto et al., 2007). Together, these measures prevent aquaculture expansion from compromising environmental integrity.

Efficient Resource Use

Sustainable use of feed, water and power also requires efficient use. Our dependency on fishmeal and fish oil has always put stress on wild fisheries. Newer methods focus on feeds with better conversion efficiency to reduce dependency on marine populations. This technique is illustrated by Integrated Multi-Trophic Aquaculture (IMTA), which mixes species of various trophic levels. Soto et al. (2007) Extractive species (like shellfish or seaweed) absorb nutrients from trash and maintain ecological balance, while given species (like prawns or finfish) are farmed together. Water management is a further important factor. Recirculating Aquaculture Systems (RAS) use less freshwater by filtering and reusing water. Along with other closed-loop systems, RAS has evolved since its mid-twentieth-century antecedents (Goddek et al., 2019) in terms of cleaning and recycling water. The RAS leads to a decrease in waste and freshwater usage in renewable aquaculture.

Animal Health and Welfare

The health and welfare of cultured species have become a central issue for sustainability. Overcrowding, poor water quality and stressful handling decrease productivity and create ecological and ethical concerns. Vaccination, thorough monitoring, and biosecurity of stock conditions are preferred over the use of heavy antibiotics, which promote antimicrobial resistance. Emerging research suggests that psychological dimensions of animal welfare extend beyond biological health. Promoting conditions for positive behaviors with no needless suffering is considered now part of responsible aquaculture (Gonzalez, 2025). In this way, aquaculture is both productive and compassionate.

Socio-Economic Responsibility

Aquaculture is more than simply food production. The sector employs an estimated 24 million individuals globally, with a substantial percentage working in coastal and rural locations. Sustainable development demands that these kinds of jobs be equitable, respectful and inclusive of individual and indigenous rights. Supply chains should be transparent and traceable to maintain ethical practice and consumer trust. Market dynamics also form socio-economic responsibility. The volumes of aquaculture production generally set pricing, and competition from substitute solutions can restrict growth. This creates pressure to balance market demand with sustainable expansion (Bostock et al., 2016). Stakeholder engagement in decision-making, regional development, and public access to natural resources ensures that aquaculture benefits societies without threatening conventional livelihoods.

Regulatory Compliance and Certification

Regulation and certification are needed tools for sustainable aquaculture. National and international rules set standards for environmental, health and safety performance. Certification schemes, such as the Aquaculture Stewardship Council (ASC) or Global G.A.P., provide frameworks for demonstrating compliance. Such systems are part of the "blue revolution," which aims to address the social and environmental issues associated with aquaculture expansion. Certification sets standards, audits compliance, labels products and institutions to enforce accountability. Such schemes are usually administered by private organizations, such as NGOs and firms, but are increasingly impacting industry practice. Nevertheless, certification has its limits; it ought to be viewed as one tool among many to promote sustainable production, rather than a complete solution (Bush et al., 2013). The challenge continues to enhance certification frameworks while making them accessible and meaningful across diverse production contexts.

Innovation and Adaptive Management

Sustainable aquaculture must be adaptable and dynamic in response to changing social and market demands. Innovation would be the key to that process. Advancements in selective breeding, disease management, feed growth and system design open up possibilities for resilience and productivity. Gleichzeitig, sustainability demands adaptive management which brings together regular monitoring, data-driven analysis and flexible responses to emerging risks including global warming and biosecurity threats (Lebel et al., 2021). By blending innovation and adaptive governance, aquaculture can be resilient and responsive in uncertain futures (Fig. 2).

Figure 2. Principles of Sustainable Aquaculture Practices (Created by author, 2025)

Common Sustainable Aquaculture Practices

Sustainable aquaculture relies on innovative practices that improve efficiency, conserve resources, and reduce environmental impact. Among the most influential approaches are Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and polyculture and co-culture techniques. Each represents a pathway for aligning aquaculture growth with ecological and socio-economic sustainability.

Integrated Multi-Trophic Aquaculture (IMTA)

Old methods constitute the basis of IMTA. Ancient Chinese and Egyptian societies experimented with integrated fish farming, utilizing farming waste to produce fish for human consumption. What is now called "Polyculture 2.0" or contemporary IMTA arose from earlier iterations of the practice, including ecological engineering (Nissar et al., 2023). Systematically combining species at various trophic levels where one species' wastes are inputs to another is how the term trophic cycling first emerged (Nissar et al., 2023). Some consider IMTA a game-changing strategy for aquaculture sustainability. Examples of extractive species that reside in these systems, alongside fed species, include aquatic plants and filter feeders. One way this structure boosts nutrient utilization efficiency is by recycling waste products into resources which support secondary crop growth. Consequently, farmers diversify their revenue streams while lowering environmental impact (Fig. 3).

In contrast, conventional polyculture places productivity above environmental mitigation. Proper planning of IMTA ensures secondary species receive extra nutrients, which limit eutrophication and habitat loss (Milstein, 2005). For instance, trash might be transformed into materials for filter feeders or aquatic weeds, which could lower fertilizer use efficiency and have an adverse ecological impact (Kumar et al., 2000). The underlying idea of IMTA is similar to the concept of the circular economy, which utilizes waste as an input to new processes. IMTA approaches waste as a resource to lessen ecological footprints and develop resilience. Consequently, the practical byproducts that aquaculture creates will last a long time (Winans et al., 2017).

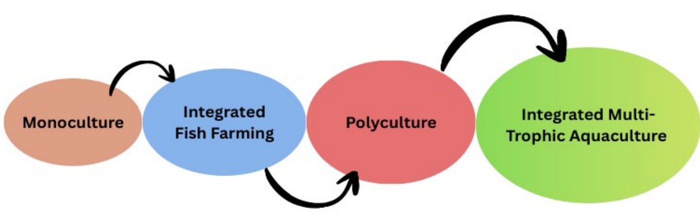

Figure 3. Revolution of Aquaculture (Created by author, 2025)

Recirculating Aquaculture Systems (RAS)

Another crucial step to sustainable aquaculture is the RAS. Since these processes are intense and closed-loop, they reuse lots of water. RAS filters and treats water from aquariums before recirculating it, with little replacement required to cover waste or evaporation (Holan et al., 2020). Raised aquatic systems (RAS) have several benefits over conventional open water or pond techniques. They're great for regions where water shortage is an issue because, first, their freshwater requirement is reduced. Water treatment and recycling at RAS conserve resources and reduce pollution entering the environment. Therefore, RAS is positioned as being an environmentally responsible model less likely to pollute and destroy habitat (Ahmed & Turchini, 2021). Along with obvious environmental advantages, RAS allows for the production in locations where there's no drinking water source, like cities. This localization cuts down on the financial and environmental burden of transporting fish, making aquaculture more inexpensive and less geographically bound. Tighter biosecurity measures are also possible in RAS's controlled environment. Animal welfare and farm profits are also improved by RAS's ability to offer consistent water quality through mechanical and biological filtration and disinfection, minimizing illness risks (Holan et al., 2020).

Polyculture and Co-culture Techniques

The growth of many different aquatic plants and animals together in a pond is called polyculture or composite culture. Polyculture, which promotes social, ecological, and economic sustainability by increasing output without improving land use, is commonly mistaken for co-culture (Jha et al., 2018). Polyculture systems, which utilize several feeding zones and natural resources, exploit the whole three-dimensional area of aquatic habitats. To boost efficiency and limit competition, compatible species are selected according to ecological niches and food preferences. Fish that feed from the surface may be kept with fish which feed from beneath and several that reside in one pond. Waste is reduced, feed is better utilized, and overall system productivity is enhanced as a result of this integration. Polyculture might have antagonistic or synergistic relationships among species. A system must work because one species enhances the habitat of a pond or increases the food readily available to another species. These synergies boost the health, general efficiency and growth rates of the fish when handled cautiously.

Stocking densities, water quality, and natural food sources must be controlled for polyculture. Periodic sampling enables farmers to monitor development and health and change feeding rates as time passes. Stocking a distinct but compatible species is crucial for the system's survival (Pant & Kumar, 2025); similarly, the acquisition & transport of quality fingerlings are equally important. Polyculture systems can adapt to market or environmental shifts, maximize resource utilization, and enhance biodiversity compared to monoculture systems. By reducing single-species dependence and enhancing output diversity, polyculture contributes to food security, farmer incomes, and ecological sustainability.

Open Ocean Aquaculture

Open ocean aquaculture is another great way to produce seafood sustainably. Aquaculture is necessary in remote and/or exposed ocean locations for a number of reasons, such as the growing need for sustainable sources of proteins and the scarcity of space along the shore, which is being made worse by aggressive renewable energy regulations aimed at reducing greenhouse gases (Ostend Declaration, 2023). This system makes use of heavy-duty submersible pens, advanced sensors, efficient undersea feeders, underwater ecosystems, accessible software, and predictive modeling to optimize fish output in deeper waters. Larger production, healthier fish, with fewer adverse environmental effects are all made possible by this technology. More profitable investment return are another benefit (Sclodnick et al., 2024). Aquaculture management has been transformed by the use of cutting-edge technology including robotics, machine learning, and artificial intelligence (AI). In order to analyze the welfare and behavior of farmed fish more precisely, bio-based robots are also being created to interact with them. These technical advancements help manage offshore aquaculture habitats sustainably and improve operational efficiency (Ma & Qin, 2024).

Use of Sustainable Feed Sources

Another important breakthrough in aquaculture is the creation of substitute feeds. Scientists are looking for feeds based on plants, insects, and algae as replacements to oil and fish meal in order to lessen the stress on wild fish supplies. The dietary composition of aquatic meals may also be enhanced by these alternatives. Organic and biodynamic aquaculture practices focus on the use of natural methods to promote the health and well-being of aquatic organisms. By avoiding the use of synthetic chemicals and genetically modified organisms (GMOs), using natural feed and fertilizers, promoting biodiversity and ecosystem services and enhancing the welfare of aquatic animals (FAO, 2018).

Water Quality Management and Conservation

Aquaculture can have significant impacts on biodiversity and habitats, particularly if not managed properly (Boyd & McNevin, 2014). Some key strategies for promoting biodiversity conservation and habitat restoration include conducting environmental impact assessments, implementing measures to minimize habitat destruction and alteration, promoting the restoration of degraded habitats, enhancing biodiversity through the use of IMTA systems and other eco-friendly approaches (Diana, 2009).

Mathematical Modelling of Aquaculture Systems

Mathematical models of aquaculture methods could be understood and improved. Equations that affect differentials enable a mathematical model of aquaculture to simulate the biological and ecological functions of a fish farming process. It represents fish biomass, feed, debris, nutrients, phytoplankton, macrophytes, and bacteria, and follows their interactions as they change, such as advancement, capture, decomposition, and recycling. These types of models support ecological harmony, optimal feed utilization, waste management, and water quality in renewable aquaculture. With quantitative system dynamics as a foundation, the model facilitates informed decision-making, leading to more effective resource utilization, reduced environmental impact, and improved efficiency over time. Such models can be utilized as resources for sustainable management methods and the development of green aquaculture systems.

The system structure, shown in Figure 3 as two primary interconnected parts, was assumed for the models. There's one system which utilizes all ten tanks. Here, we explain the species being bred and how it is raised in the tank or tanks. This fish receives the pellet food daily at the very same time. The metabolic processes of this community produce wastes. Since the water entering the pond and the water leaving the phytodepuration canal will be the same, they ought to be treated as one entity that impacts the remainder of the system the same way. Plant life in the pond includes submerged and floating plants and phytoplankton, which feed the plants and release wastes. Phosphorus and nitrogen are presumably present and in amounts adequate for plant development, but not treated as individual nutrients. The mineralization process at first happens in a microbiological pool junk in a pond. The model simulates the continuous introduction of nutrients and debris from the tanks to the pond, but not the hatchery processes. Debris from the tanks to the pond in every time step is carried by a network of tubes connecting the two subsystems. We assume that their movement is constant as time passes. With this kind of vigorous metabolism rate, there'll always be lots of debris in the tanks. Nevertheless, phytodepuration, along with microbial pool processes in the pond, rapidly breaks it down. Care has to be taken when selecting which fish species to raise during mating season because this might be vital for the plant's financial health. Growth parameters of the fish were followed in the frame of the other experimental findings, too. Additionally, for a sensible choice, water temperature is the most significant factor. Salmonids (trouts) are sometimes preferable to cyprinids (carps) that develop during warmer temperatures and contain ornamental fish, owing to their economic value. Strurgeons can also be intriguing options with high financial return. All these factors above also indicate that this kind of aquaculture facility could be utilized year-round for the hatching of different fish species.

Use of Resilient Aquaculture

Impacts on aquaculture and fisheries Fish cultivation, extinction of species, susceptibility to disease, and fisher folk employment are all impacted by climate change. The physiology side of the issue comprises migration to a favorable zone, developmental and breeding cycles, embryonic growth, hypoxia, and changes in organisms, cells, molecules, and organelles. Income, employment, malnutrition, and the decline in anadromous fish production are all included in the socioeconomic component. The abiotic stress and its interactions with other stresses contribute to climate change. The most widely used definition of resilience by Walker et al. (2004). The capacity of a complex network to tolerate shocks without compromising its functionality and to reorganize after being disrupted is known as resilience. To maintain high production of fish with minimal or no adverse effects on the environment, there is a need to adapt weather change. Solutions to climate change that sustainably improve the productivity of aquaculture have been developed. Similar to agriculture, aquaculture has also been modified to suit the shifting climatic conditions due to technological innovativeness. The presence of robust aquaculture systems is capable of supporting the ecological, social, and economic benefits, even confronting the significant weathering. Climate-smart aquaculture has been identified as a vital measure for mitigating climate change, and this project aims to enhance efficiency and improve ecosystem dependence, thereby making aquaculture more resilient to climate change.

Nadarajah & Eide (2020) has revealed that species of shrimp have better adaptability to climate change, including seawater intrusion, warmth, and reduced fish meal supply, compared to fish species, like salmon, carps, and catfishes. Conversely, aquaponics is an innovative farming system that combines fish rearing with Growing vegetables hydroponically. This system endure climate effects, water shortage, waste management, and soil erosion. Integrated farming strategies consisting of numerous elements (farming animal's species, and crops, in addition to fish farming) can be utilized to enhance the efficiency of aquaculture. Another element of climate change tolerance in aquaculture is selective fish breeding, but this tool is yet to be fully developed. Selective breeding can build resistance to temperature rise, resistance to diseases and other attributes. A healthy fish population is the ultimate goal of selective breeding. It has mostly been carried out on shrimp and bivalves. Aquaculture, whether it be freshwater aquaculture, marine farming, inland saline farming, as well as aquaculture-based fisheries/reservoir fisheries, must be carried out and dispersed in a variety of latitudes that encompass tropical, subtropical, and temperate climate regions and typical settings. Figure 2 illustrates the different resilient responses to climatic change.

Organic Aquaculture Practices

Organic culture system is an environmentally favourable and sustainable system of fish cultivation that utilizes synthetic chemicals, antibiotics and artificial feed additives. Instead, it depends on natural inputs, which include organic manures, plant-based feeds and biological disease and water quality management. This type of system encourages ecological balance, whereby polyculture and vermicomposting are incorporated (as part of organic waste use in the system), where fish farming is coupled with the recycling of organic wastes, to generate natural fertilizers. Strict certification standards govern organic cultivation systems to ensure the traceability and purity of the produce. These systems also reduce pollution by producing chemical-free and healthier fish, thereby helping to conserve the environment and providing more value in the market, considering the increasing demand for organic products. The most significant production, namely nineteen tons of Indian three major carps per hectare, is realized under the organic aquaculture. The organic culture system has another advantage, besides fish yield, in the form of vermicomposting production. An organic culture system can be used to produce a net worth of 106,218.75 USD a ten-year project duration, an expected two-year payback period, with an IRR of 51%. The most valuable methods that are currently available are the production of fish, vermiculite, and natural cultivation. The price for which the naturally grown fish will be sold is the most delicate component of the investment in organic fish farming (Tusche et al., 2011; Xie et al., 2013).

In the aquaculture industry, there is a steady rise in demand for fish and fishery products that are produced organically (Gould et al., 2019; Sicuro, 2019). Around 25,000 tons are produced annually by organic fisheries worldwide, with 14,000 tons coming from Europe and 8,000 and 3,000 tons from Asia and America, correspondingly (Willer et al., 2024). The adoption of a comprehensive strategy of natural and organic fish feeds is necessary for the nation's aquaculture to flourish sustainably (Vasilaki et al., 2023; Muller et al., 2017). Chemicals and pesticides should not be present in the input. Freshwater finfish farming in India is dominated by three major Indian carps: the Catla (*Catla catla)* the Rohu *(*Labeo *rohita*), and the Mrigal (*Cirrhinus mrigala*). Their production has already reached a commercial level in the Indian subcontinent. Over 70% of India's entire inland aquaculture production and over 80% of the world's production of major Indian freshwater fish species comes from them (Nandeesha et al., 2001; Roy et al., 2021).

Use of Artificial Intelligence in Sustainable Aquaculture

Technologies related to computer vision and machine learning have demonstrated enormous potential in processing large amounts of data collected in fisheries sector. Using AI algorithms, fish cultivators will be able to obtain important information about the way fish grow, their feeding behavior, and how the environment influences the well-being of fish (Fig. 4). Such algorithms are able to identify and forecast anomalies, diseases, and indicators of stress in order to prevent losses and address the causes of a particular health problem. A major way in which AI has been used in the field of aquaculture is through intelligent sensing systems. Such systems employ numerous sensors, cameras, and data analytics to constantly monitor live data on water quality parameters, Dissolved oxygen, temperature, pH, and fish behavior (Mustapha et al., 2021). AI algorithms examine such data to discover the non-optimal conditions and notify farmers to modify feeding schedules, drinking water treatments when necessary. Furthermore, AI-based models can optimize feeding schedules and waste reduction. The best feed formulation and feeding regimes can be identified from existing historical information on fish growth and feed intake, leading to increased growth rates and minimum environmental effects through the use of machine learning algorithms. An additional crucial area of AI in fish farming is disease testing and preventions. AI algorithms identify illness symptoms, parasites or an alteration of appearance and behavior in fish before humans notice anything with picture analysis and pattern recognition. This enables the timely diagnosis of illnesses and treatment, leading to decreased antibiotic and chemical usage and the overall welfare of the fish. To conclude, the application of AI in fish rearing and health monitoring is promising for the sustainability of the aquaculture business. AI can now assist fish farmers to improve welfare, environmental impact, productivity, and their operations of farmed fish by analyzing information, determining patterns and making predictions. Nevertheless, far more must be done on AI, with greater sharing of cooperation and information between researchers, business actors, and policymakers, to recognize AI at its full potential and produce a viable aquaculture sector (Mandal & Ghosh, 2024).

Figure 4. Common Aquaculture Sustainable Practices (Created by author, 2025)

Conclusion

Sustainable aquaculture methods are becoming more important to achieve both environmental and financial objectives as the demand for fish around the world keeps growing. Future regulations for sustainable aquaculture must prioritize reducing negative effects on the environment while enhancing productivity and protecting the health and welfare of cultivated species. Going forward, sustainable aquaculture must corporate technological innovations such as precision aquaculture, AI-models as sensors and real time monitoring systems, and renewable energy-powered RAS to overcome environmental footprints. However, along with technologies use and scaling alternative feed sources like insect meal, simple proteins, and algae to decrease dependence on wild fish stocks and terrestrial agriculture; moreover, there is a pressing need for more holistic regulatory and certification frameworks that incorporate not only environmental and animal welfare criteria but also social equity and community participation, especially in small-scale systems; also critical are adaptive, context-sensitive intensification strategies that take into account local socio-ecological conditions to avoid overuse of water, nutrient pollution, or collapse of ecosystems; finally, stronger interdisciplinary research combining ecology, economics, policy, and social sciences will be essential to design aquaculture systems resilient to climate change, resource competition, and shifting market and consumer dynamics, ensuring that aquaculture contributes positively to food security, livelihoods and ecosystem health.

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CHAPTER II

GLOBAL TRENDS AND CHALLENGES IN AQUACULTURE SUSTAINABILITY

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Introduction

Global food security depends on sustainable aquaculture, especially in context of population growth, climate change, and environmental degradation. (Bank et al., 2020). The global population is rapidly rising, and with it the global appetite for fish. Global production of cattle, poultry, and pigs has grown during the last 60 years, with poultry outpacing the others. Concern over limited and increasingly over-taxed agricultural resources has governing bodies turning to the oceans to supply their growing populations with protein, while climate and health-conscious consumers view to fish as a healthy, sustainable alternative to red meat or poultry. Around 1985, aquaculture became the sole animal-producing sector in the world. Within rising population and economic development, demand for aquatic food products is projected to match or surpass that of other animal-based proteins (Belton et al., 2020; Costello et al., 2020). To meet the demand for food from a growing global population, aquaculture production is under great pressure to increase as capture fisheries have stagnated. As capture fisheries remain stagnant and global fish stocks are overexploited, aquaculture has emerged as the primary means of meeting protein demand. Since the late 1980s, aquaculture production has increased by 500% (Yuan et al., 2019). In 2018, production reached 82.1 million tonnes, contributing 46% of global fish production. Between 1990 and 2018, global food fish consumption grew by 3.1% annually (increased by 122%), outpacing all other animal protein sources (FAO, 2020).

Fish account for about 20% of the animal protein utilized per capita by more than 40% of the world's population, while aquatic species represent 17% of all animal protein consumed worldwide.

Global food fish consumption growth (3.2%) exceeded the rise of meat consumption from all terrestrial animal production sectors combined (2.8%), with the exception of poultry, reflecting dietary shifts. According to Schar et al. (2020), aquaculture accounts for 8% of the animal protein consumed by humans worldwide, and its per capita consumption is rising more quickly than that of meat and dairy. Fish farming has grown at the fastest rate in Asia and a few other nations to satisfy the growing demand for human consumption. With over 90% of the world's production by volume and 79% by value, Asia leads the world in production. China alone was responsible for 61% of global production in 2016. Approximately one-third of all capture and aquaculture fisheries items consumed by humans globally come from China's aquaculture production output (FAO, 2018). China leads the pack with 32.7 million tons, producing over 60% of the world's output. Traditional methods, population and economic growth, laxer laws, and export demand are the main drivers of the region's growth; more aquaculture fish are produced in China, India, Vietnam, Bangladesh, and Egypt than wild fish. While demand for fish and seafood is still growing, aquaculture growth in North America and Europe, which peaked in the 1980s and 1990s, has since stalled due to competition and stronger restrictions (Ibrahim et al., 2020). Europe's consumption of fish and aquaculture products (FAPs) increased significantly to 24.36 kg per consumer in 2018, and consumer spending on FAPs reached €56.6 billion in 2019. Romania showed the highest growth (8%), while Italy, Spain and France were the largest markets by value. per capita spending average €110, peaking in Portugal (€371) but remaining low in Eastern countries like Hungary (€15) and Bulgaria (€27). Growth was stronger for aquaculture products, through captured fisheries still dominate 74% of consumption. The FAPs' self-efficiency in Europe was roughly 42.5% (EUMOFA, 2020).

Seafood products are predicted to play a significant role in fulfilling the overall protein demand, which is predicted to double by 2050. Aquaculture enhances the United Nations Sustainable Development Goals (SDGs) in addition to output. It was a major contributor to poverty alleviation, nutrition improvement, and economic growth worldwide. Importantly, aquaculture is seen as a key strategy to strengthen resilience in global food systems against climate change and rising protein demand (Troell et al., 2014). The loss of wild fish supplies, increased demand for healthful protein, better farming methods, and the creation of enriched feed have all contributed to aquaculture's transformation from a traditional, noncommercial activity to a significant food supply. Up to 80% of the world's finfish and shellfish supplies have been depleted, making aquaculture crucial for supplying safe and sustainable substitutes. By 2014, aquaculture has produced 26.1 million tons of aquatic algae and 70.5 million tons of edible fish, helping to boost total fish consumption from 5% in 1962 to 49% in 2002 (Pauly & Zeller, 2017). To prevent resource depletion, attain ecological balance, and make effective use of resources, sustainability is crucial in all industries. Numerous worldwide environmental, social, and economic issues are arising as a result of society's worsening relationship with the environment at an accelerated rate. Maintaining ecological balance requires both economic development and improvements in environmental quality, which makes ensuring sustainability difficult. Selecting more sustainable goods or services is one way that people may contribute to sustainability.

GLOBAL TRENDS IN AQUACULTURE

Species diversity

The global food system can become more resilient if aquaculture has a high species variety. Aquaculture is a varied food production system. The aquaculture industry as a whole may benefit from high species diversity. By rotating different species in accordance with seasonal fluctuations, polyculturing multiple species in the same farming system, or cultivating the most suitable species in various farming environments, species diversification can theoretically increase farming efficiency (Thomas et al., 2021; Newton et al., 2021). In terms of economics, species diversity can assist the industry in expanding its market base and overcoming market satiation. In the face of disease outbreaks, market volatility, and climate change, species diversification is becoming more widely acknowledged as a critical tactic to improve aquaculture growth, resilience, and long-term sustainability (Metian et al., 2020). Therefore, both the scientific and policy sectors generally support species diversification as a key tactic for the development of sustainable aquaculture (Boyd et al., 2020; García-Márquez et al., 2021; Oboh, 2022).

Despite its endorsement in policy and scientific communities, many diversification efforts have shown limited long-term success, as the private sector often prioritized fast-growing, high- value species (Cai et al., 2022). A global assessment (1950-2020) using the "effective number of species" indicator revealed that while aquaculture exhibits high diversity at the global level, national level diversity often low, with nearly half of countries showing no significant diversification. Moreover, recent decades indicate a slowdown in diversification and shift towards species concentration, similar to terrestrial farming. To reverse this trend, Public interventions are crucial to lower costs, enhance benefits, and promotes viable diversification pathway. Since patterns vary widely across countries, knowledge exchange and evidence-based policymaking are essential to guide diversification strategies, improve data quality, and strengthen aquaculture's long-term sustainability (Cai et al., 2023).

Intensive farming and production systems

The growth of aquaculture is currently moving toward more profitability and improvement of aquatic products. Driven by limited availability of suitable sites and increasing demand, aquaculture is shifting towards more intensive farming systems. These systems aim to maximize production per unit area but require advanced management to address environmental impacts such as waste management, water quality, and disease control. Diverse production and livelihood systems known as aquatic agricultural systems (AAS) can be found along coasts, estuary deltas, freshwater floodplains, and inland lakes and rivers. Increasing food production from existing agricultural land is frequently seen as the most practical way to address food security, and intensification is becoming a more effective strategy for doing so than expansion (Attwood et al., 2017). Intensification allows higher production, efficiency in land/water use, improved disease control (in closed systems), and helps meet food security goals.

Table 1. Intensification: As a Global Trend and Challenge

Intensification as a Global Trend	Sustainability Challenges of Intensification
Increases in stocking densities per unit area or volume	Increased reliance on fishmeal, soy, and other feed ingredients
Contributes to global food security as protein requirements increase	Effects on environment: water contamination, eutrophication, habitat erosion
Zoning is used to optimize production and improve efficiencies through technology (aeration, RAS, formulated feed, automation)	More expensive production that leaves small farmers less competitive.
Allows for 12-month, mass supply to the domestic and export markets	Higher disease outbreak possibilities under high density arrangements
Fosters an evolution in farming methods as well as feed substitutes	Increased energy consumption and carbon footprint (e.g., in high-density recirculating systems)
May relieve pressure on wild catch fishery if conducted in a sustainable manner	Socioeconomic inequality: the big farms and the smallholders
Aids integration into world trade and value	Potential loss of traditional, low-impact farming practices

Source: Created by author, 2025 using data extracted from Attwood et al., 2017.

Emerging Technologies in Aquaculture

Aquaculture plays a crucial role in ensuring nutritional security and livelihoods as capture fisheries stagnate. Rising demand for quality protein has driven a shift from traditional to semi-intensive and intensive systems, improving yields and incomes but creating challenges such as eutrophication, monoculture risks, rising feed costs, disease outbreaks, and environmental concerns. To address these issues, sustainable aquaculture models emphasize eco-friendly, economically viable practices that integrate species across trophic levels, reducing risks of monoculture and enhancing system resilience. Integrated multi-trophic aquaculture and aquaponics combine species with complementary ecological roles to optimize nutrient use and reduce waste. Such systems enhance resource efficiency and environmental sustainability.

Table 2. Integration with Other Production Systems and their challenges

Integration with Other Production Systems	Challenges/Limitations
Shift from monoculture to integrated systems (e.g., RAS, IMTA, BFT, aquaponics, polyculture)	High initial investment and operational costs
Combines species at different trophic levels to optimize nutrient recycling and reduce waste	Technical complexity and management skill requirements
Enhances resource efficiency (water, feed, land use) and reduces environmental footprint	Limited awareness and adoption, especially in rural areas
Diversifies production, reducing risks of monoculture and disease outbreaks	Potential biosecurity issues if not managed properly
Supports eco-friendly and climate-resilient aquaculture practices	Market limitations for some co-cultured or low-value species
Revives traditional integrated systems (e.g., paddy–fish, livestock–fish) with modern innovations	Policy and regulatory gaps in promoting integrated aquaculture
Provides additional livelihood opportunities for small-scale farmers	Scaling up remains difficult compared to intensive monoculture systems
Aligns with global sustainability goals (SDGs) by improving food security and environmental health	Need for more research, data, and evidence-based guidelines for wider implementation

Source: Created by author 2025, using data extracted from Ahmad et al., 2022; Nissar et al., 2023; Laktuka et al., 2023.

Innovation plays a crucial role in advancing aquaculture. Traditional integrated approaches (e.g., paddy–fish, livestock–fish) and modern innovations such as recirculatory aquaculture systems (RAS), integrated multitrophic aquaculture (IMTA), biofloc technology (BFT), and polyculture are increasingly promoted as sustainable pathways. Technologies such as precision aquaculture using AI and sensors, blockchain for traceability, and automated feeding systems are being adopted to increase productivity, sustainability, and transparency. These models offer synergistic benefits for productivity, resource efficiency, and environmental health, making them particularly suitable for small-scale farmers in developing regions while supporting global aquaculture sustainability (Laktuka et al., 2023).

Traditional integrated approaches

Traditional aquaculture relies heavily on integrated systems that use by-products, manure, and agricultural residues, with peri-urban ponds, often nourished by municipal effluents. Fertilized ponds are cost effective, as waste can recycled within the system, reducing external inputs (Boyd et al., 2020). However, excessive feeding leads to nutrient buildup (nitrogen, phosphorus, other minerals, and organic wastes), which lower DO and harms cultured species. Aquaculture wastes are categorized as liquid (wastewater and discharge) and solid (feces, feed, and other solid materials) (Henares et al., 2020; Das et al., 2023). While ponds can naturally process some residues, productivity is limited by solar radiation and fertilization efficiency. Yields range from 4–6 t/ha with fertilization and up to 8–10 t/ha with aeration and feeding. To boost production, balanced commercial feeds from plant and animal ingredients are required, though feed sustainability, import dependence, and food safety pose concerns. Advances in filtration, recirculation, and water treatment can enhance water reuse, yet land and water resource constraints remain major challenges. Low-intensity pond systems generally minimize environmental impacts as wastes are processed on-site, supporting sustainable production (Edwards, 2015; Boyd et al., 2020).

Recirculatory aquaculture systems (RAS)

Recirculating aquaculture systems (RAS) are intensive, closed-system aquaculture setups that re-use 90–99% of the water, reducing land and water needs compared to flow-through system (Ahmad et al., 2022; Tom et al., 2021; Badiola et al., 2012). According to their water exchange rates, they are divided into "next generation" or "innovative" systems (<0.1 m3/kg feed) and traditional recirculation (0.1–1 m3/kg feed). RAS units usually consist of water pumps, oxygen supplies, filtration systems, solid waste removal, wastewater treatment, power generators, rearing tanks, and disinfection systems (such as UV). (Zimmermann et al., 2023, Ahmad et al., 2022). The main advantages are high density production, improved management of pathogens and water quality, and reduced environmental impacts (Henares et al., 2020). However, challenges includes high initial and operating costs, energy-intensity, system complexity, sludge accumulation, and risk from power failures (Kamali et al., 2022). Although RAS is environmentally friendly, its contribution to a circular bioeconomy is limited since nutrients are often not recycled; integrating RAS with constructed wetlands, biofloc technology, or polyculture is being explored to enhance sustainability (Tom et al., 2021).

Integrated multitrophic aquaculture (IMTA)

Integrated multitrophic aquaculture (IMTA) involves farming multiple species- such as fish, shrimp, shellfish, algae or sea cucumbers- within the same system to recycle nutrients and create a balanced ecosystem (Park et al., 2018). Integrated multitrophic aquaculture (IMTA) is considered an advanced form of polyculture. In IMTA, fish or shrimp cultivation s supplemented with algae that absorb inorganic nutrients, and deposit feeders such as shellfish or sea cucumbers that utilize organic wastes (Sanz-Lazaro & Sanchez-Jerez, 2020). IMTA establishes ecological links wherein one species benefits from the byproducts of another, as opposed to polyculture, which just entails rearing many species in the same body of water. In order to encourage resource and energy efficiency and reduce pollution risks, IMTA can be implemented in open-water systems, tanks, or land-based ponds. It adheres to the concepts of the circular economy

(Henares et al., 2020). However, creating a balanced system is a significant challenge as it necessitates in-depth understanding of each species' unique biological requirements, feeding habits, oxygen consumption, and trophic level. Research indicates that IMTA enhances environmental, economic, and social sustainability by boosting ecosystem resilience and increasing the amount of protein produced per unit of food (Alexander et al., 2016). However, obstacles include the difficulty of striking a balance between species requirements, high setup and operating expenses, a dearth of research, and low public awareness. With more scientific research, governmental backing, and proof of financial gains, IMTA has the potential to become a popular sustainable aquaculture technique (Nissar et al., 2023).

Biofloc technology (BFT)

A controlled environment system comprising suspended phytoplankton, heterotrophic bacteria, algae, protozoa, feces, and leftover food is used in biofloc aquaculture, sometimes referred to as biofloc technology (BFT), to provide an organic fish diet (Ogello et al., 2021). BFT was developed in the 1970s with the aim of addressing the two main environmental problems in aquaculture, and these are protein extraction and wastewater recovery (Das et al., 2023). For these reasons, the BFT could be one of the primary aquaculture pathways to a sustainable future (Mugwanya et al., 2021; Khanjani et al., 2023).

- Feed expenses are reduced by 30% because less feed is needed.
- Water filtration is improved by natural microbial biomass
- Some bacterial species help trap CO2 from the atmosphere.
- There is little to no external water exchange
- Cultured aquatic creatures have improved growth, function, and immunity

Table 3. Advantages and disadvantages of Biofloc technology (BFT)

Pros of BFT	Cons of BFT
Uses recycled waste materials to create an in-pond food supply that is high in nutrients.	Energy-intensive; high construction and operating expenses
Improves sustainability by recycling trash and lowering reliance on outside feed.	demands a high level of technical proficiency to oversee
Able to use plant-based proteins for environmentally friendly manufacturing	Outdoor systems that are sensitive to light, season, and location
Improves nutrient utilization and waste disposal to lessen the impact on the environment.	Danger of declining water quality (DO, pH, and ammonia) if improperly observed
encourages IMTA integration, increasing the financial gains	Need a lot of aeration to keep the system balanced.
Tanks or ponds can be used with this adaptable design.	Biofloc accumulation necessitates cautious handling.
encourages aquaculture to adopt a circular economy	Geosmin and 2-methylisoborneol's off-flavors (muddy/earthy taste) might make them less acceptable to consumers.
Possibility of creative research and policy assistance	Skepticism among consumers as a result of reliance on nutrients generated from waste
promotes environmentally friendly aquaculture methods	Gaps in our understanding of microbial operations; further study is needed

Source: Created by author 2025, using data extracted from Das et al., 2023; Khanjani et al., 2023.

Polyculture

Polyculture is the practice of cultivating two or more species in the same fixed place, such as fish and plants, plants and animals, or even aquatic and terrestrial species.(Amoussou et al., 2022). The practice of polyculture originated in China, where many carp species were raised in a single pond or where rice and fish farming were integrated (Sanz-Lazaro & Sanchez-Jerez, 2020). The basic principle of polyculture remains the same, despite recent attempts to mix different aquatic species: the aquatic organisms being cultivated must occupy different ecological niches rather than compete with each other for resource. Benefits of growing several aquatic organisms at once include increased resource efficiency, financial gains from all species raised and sold, and better water quality (Stickney et al., 2013).

Disease Management and Biosecurity

Disease outbreaks pose significant risks to aquaculture productivity. Enhanced biosecurity measures, vaccination, and health monitoring technologies are increasingly deployed to manage and prevent diseases.

With tactics focusing on prevention, early identification, and efficient management, biosecurity in aquaculture is crucial to preventing disease outbreaks that can result in significant financial and environmental losses.

There are three types of biosecurity measures:

1. Biological (boosting immunity and lowering disease risk),
2. Operational (feed management and cleanliness procedures),
3. Physical (preventing pathogen invasion and wild fish infiltration).

Artificial intelligence and *sensors* are examples of emerging technology that increase the effectiveness of biosecurity. Although biosecurity improves food safety, environmental protection, and disease prevention, issues like implementation costs and possible environmental effects still exist. Coordination of response strategies, risk assessment, and sustainable practices are essential for effective management. In the end, incorporating effective, economical, and ecologically conscious biosecurity measures is essential to aquaculture's long-term viability in order to preserve ecosystems, maintain animal health, and guarantee safe, high-quality produce (Aly & Fathi, 2024).

One of the sectors with the quickest rate of growth is aquaculture, which is spreading both domestically and internationally. Disease prevention is a persistent problem with serious economic and environmental consequences, just like in traditional animal farming. However, recent years have seen impressive advancements in the creation of aquaculture vaccinations, providing long-term fixes for enduring health problems that threaten robust aquaculture production. Vaccines created with the aid of modern, sophisticated molecular technology may be a useful treatment for infections that cause disease in aquatic creatures (Mondal & Thomas, 2022). Following the recent introduction of nanotechnology, biotechnology, and artificial intelligence in the -omics age, these developments are typified by advances in improved vaccine-delivery methods, enhanced species-specific accuracy, and vaccine development innovations (Tammas et al., 2024).

Cost-Effective and Sustainable Feed Development

Farmers in fisheries try to minimize the inclusion level of costly feed components and substitute them with less expensive ones in order to lower feed costs without sacrificing growth. A diet rich in protein increases aquaculture production and minimizes feed expenses (Wang et al., 2021). Feed is a significant cost of operation and sustainability issue, with growing efforts to replace fishmeal and fish oil with substitute, sustainable ingredients. The incorporation of various micronutrients can boost feed efficiency and lower feed costs, which will help overcome this obstacle and create high-quality, reasonably priced feed (Rohani et al., 2022). The aquaculture sector is increasingly searching for a nutritional, economical, and sustainable substitute for fish meal (FM). This is because there is an increasing difference between the supply of fish meal and the industry's growing demands (AlMulhim et al., 2023). The need to develop sustainable feed based on non-food resources is necessary since the increase in demand for animal protein will also lead to an increase in feed ingredients like fishmeal and fish oil, which are scarce (Solberg et al., 2021).Fish feed formulation has been modified by the increased demand for sustainable food supplies caused by the expansion of the world's population.

Historically, the main ingredients were fishmeal and fish oil, but increasingly environmentally friendly alternatives such as mealworms, Black Soldier Fly, and plant proteins and oils are replacing them. Plant proteins such as soybean are cheap, insect-based proteins utilize organic waste to enhance sustainability, and fishmeal has an improved mineral quality. Rice protein meal also utilized as sustainable source (Asad et al., 2025). Fishmeal and soybean are being phased out because of their high prices, scarcity, and detrimental effects on the environment, including deforestation and overfishing. Fish oil, vegetable oil (like flaxseed oil), and algal oil all have unique benefits and drawbacks in terms of digestion, cost, and the amount of omega-3 and omega-6 fatty acids they contain. The shift toward these alternatives is driven by the need for more sustainable, efficient, and cost-effective production methods that also improve the nutritional quality and appearance of farmed fish, which is a vital source of protein and essential fatty acids for human consumption (Zlaugotne et al., 2022). Because they are more affordable, more environmentally friendly, and have higher nutritional content, sustainable substitutes such as plant proteins, insect meal, algae, and animal byproducts are being used. Difficulties still exist, nevertheless, such as impediments to consumer adoption, regulatory limitations, anti-nutritional factors, and digestibility problems.

Antimicrobial use in aquaculture

Non-therapeutic antimicrobial usage is frequently used to enhance growth and make up for poor husbandry methods in intensive livestock and aquaculture production, which has been driven by the worldwide need for animal protein (Van Boeckel et al., 2017). Currently accounting for over 8% of global animal protein consumption, aquaculture has grown at a faster rate than the meat and dairy industries. Antibiotic usage has, however, surged as a result of this progress, raising serious concerns over antimicrobial resistance (AMR) and ecological health. A thorough investigation indicates that 10,259 tons of antimicrobials were used in aquaculture globally in 2017. It is anticipated to have risen by 33% to 13,600 tons by 2030, mostly as a result of Asia-Pacific countries, particularly China. Aquaculture has the highest intensity per biomass of any food industry, with catfish and trout exhibiting the highest usage rates, although making up only 5.7% of the world's total antimicrobial consumption. Crucially, every medication class utilized in aquaculture is regarded as medically relevant, which increases the possibility of the emergence of resistance (Schar et al., 2020). The extensive use of antibiotics in cattle and aquaculture, whether for prevention, treatment, or growth enhancement, has sped up the development of resistant microorganisms in both land and aquatic systems. This poses a major danger to human health, food security, and animal welfare. Aquaculture systems are especially vulnerable because antibiotics may travel rapidly across the environment, altering microbial populations and creating reservoirs for resistance genes that can spread among humans, animals, and ecosystems. Despite these risks, the lack of global data on antibiotic use in aquaculture continues to hinder the development of effective stewardship and policy frameworks. AMR is a serious public health concern as the careless use of veterinary medications not only promotes the spread of resistant bacteria but also causes more extensive harm to people, animals, and the environment (Ibrahim et al., 2020).

Table 4. Advantages and Disadvantages of using Antimicrobial in Aquaculture

Aspect	Advantages	Disadvantages
Disease Management	Efficient in lowering mortality by treating and avoiding bacterial infections.	Antimicrobial resistance (AMR) brought on by overuse renders treatments useless.
Growth & Productivity	Growth rates and feed efficiency may be improved by sub-therapeutic dosages.	Long-term production is decreased and treatment expenses are raised by resistant diseases.
Economy Impact	Stabilizes yields and reduces the monetary losses caused by disease outbreaks.	Stricter restrictions, denied exports, or AMR might all result in higher costs.
Food Security	Encourages increased aquaculture output to satisfy the growing demand for protein.	Consumers are concerned about food safety owing to residues in fish tissue.

Environmental Impact	During disease outbreaks, short-term productivity aids in supply maintenance.	Antimicrobial residues damage ecosystems, disturb microbiomes, and spread in water.
Trade & regulation	Guarantee steady supply to both home and foreign markets.	Antimicrobial residues are restricted in several nations, which hinders commerce.

Source: Created by author 2025, using data extracted from Ibrahim et al., 2020; Schar et al., 2020.

CHALLENGES IN AQUACULTURE SUSTAINABILITY

Socio- economic challenges

Socio-economic and environmental assessment (SEEA) deal with identify challenges to social, economic, and environmental issues and providing management solutions. Aquaculture is expanding to meet growing demand as capture fisheries remain unsustainable. But there are drawbacks to this rapid growth as well: weighing the advantages for the economy and food security against ecological, socioeconomic, and environmental issues (Bhari & Visvanathan, 2018).

Due to the lack of comparable data to examine social, economic, and ecological effects in various regions and aquaculture systems, evaluating sustainability in aquaculture is difficult. Although the FAO provides solid production data, there is little information on social, economic, and environmental aspects, particularly in poor countries (Garlock et al., 2024). The problem is solved by creating APIs that enable consistent data collection on a variety of topics related to aquaculture sustainability, facilitating international comparisons. An expansion of Fishery Performance Indicators (FPIs), APIs may be used to analyze sustainability issues for specific systems or areas as well as on a global scale (Anderson et al., 2015). The 88 outcomes measures across 19 categories in the APIs can be used to create social, economic, and environmental performance metrics. These issues are important, but they also present an opportunity to develop new strategies and alter laws that can improve the sustainability of aquaculture. Aquaculture is less profitable due to market competition from wild fisheries and other food sources. Further development and sustainability initiatives may be more difficult to implement if land and water supplies are limited. New technologies are badly needed to improve sustainability and efficiency, even though they are often undeveloped. If the industry is to continue to be adaptable and endure throughout time, stakeholders must work together to overcome the complexity of these concerns (Hieu et al., 2023).

Technological and management challenges

Aquaculture is an essential sector of food production that significantly affects global food security. Because of its rapid expansion, the sector needs to balance innovation, environmental preservation, and economic rewards in order to achieve sustainability. Technological breakthroughs such as recirculating aquaculture systems (RAS), genetic engineering, integrated multitrophic aquaculture (IMTA), and others have significantly improved the aquaculture business (Badiola et al., 2012). These technologies have revolutionized the agricultural sector by increasing production and tackling problems including disease prevention, resource optimization, species diversification, and reduced environmental impact. The long-term environmental repercussions of adopting these technologies, such as potential ecological dangers, habitat loss, pollution, and genetic influences on wild populations, must be carefully considered (Boyd et al., 2020). Furthermore, it is impossible to overlook aquaculture's economic component. Even while technology advancements might increase profits and productivity, their implementation typically necessitates significant financial investments and regulatory compliance. To create regulatory frameworks and incentive programs that support sustainable aquaculture practices, policymakers and industry stakeholders must work together (Ohia, 2025).

Despite its many benefits, low-cost technologies are not widely adopted, especially in developing nations, due to a number of socioeconomic hurdles. The inability of small-scale fishermen and aquaculture producers to invest in new technologies due to their low financial resources is one of their concerns. Even though low-cost technologies are meant to be affordable, many fisherman may still face severe financial difficulty due to the initial setup fees of gadgets like solar power systems or Internet of Things sensors (Saidu, 2025). Moreover, small-scale fishermen typically lack access to financing and credit alternatives that may assist them in meeting the expenses associated with adopting new technology (Hungevu et al., 2025). One of the main obstacles to aquaculture's adoption of artificial intelligence (AIoT) and the Internet of Things is scalability. Small-scale farms are unable to operate these systems due to the high costs and complexity of data handling (Sung et al., 2021). The lack of qualified personnel in data science, machine learning, and IoT administration is one of the main problems. Employee development and targeted training are required to close this gap and guarantee the successful use of AIoT in aquaculture (Matin et al., 2023). Infrastructure and environmental issues provide a hurdle to aquaculture AIoT. Even though distant farms usually lack a reliable electricity supply and internet to facilitate real-time data consumption, energy-consuming technologies might jeopardize sustainability. Other barriers to widespread use include high costs, communication issues, and the equipment's durability in harsh conditions (Tina et al., 2025).

Policy and Governance issues

Europe's aquaculture development has faced governance, environmental sustainability, and social acceptance challenges. Transparency issues, limited emphasis on the environmental aspects at the expense of social dimensions, and minimal stakeholder engagement are among the most significant gaps. Besides legal changes aimed at sustainability, strategic frameworks highly emphasize certification, labeling, and communication to promote public trust. But value conflicts give rise to conflict, and most often, governance does not have the mechanisms for inclusive decision-making. Opportunities exist in eco-certifications and hybrid governance, but no substitute for good public policy, transparency, and trust. To increase aquaculture's long-term acceptability and sustainability, there is a need for a pragmatic, context-sensitive approach that includes social, economic, and environmental practices. Social acceptability problems arise from top-down approaches that frequently shape aquaculture policies, ignoring local realities. A shift to local and regional governance may promote conflict resolution, improve participation, and integrate policies with community needs. Aquaculture development must be sustainable and inclusive, with clear, open, and quantifiable goals and integrated impact assessments that take social and economic factors into consideration.

FUTURE DIRECTION AND OPPORTUNITIES

Aquaculture is now the world's largest source of aquatic food, and its future will be influenced by methods that boost output while lessening the impact on the environment and enhancing social consequences (Chopin et al., 2024). Farming also includes planning, developing, and running aquaculture systems, sites, facilities, and procedures, as well as production and transportation, as well as individual or corporate ownership of the stock being raised (Najdegerami et al., 2023).

Scale sustainability intensification with strong governance and fiancé

Policy, fiancé, and technical assistance for smallholders must be combined with intensification to increase global aquaculture production while limiting adverse effects. (Chopin et al, 2024). Large investment prospects in sustainable aquaculture are highlighted by recent World Bank evaluations, which also stress the necessity of supportive regulations and blended fiancé in order to expand responsible systems.

Replace wild caught fish meal with alternative feeds

A major leverage point is feed, which can lessen cradle to farm consequences and strain wild fisheries by reducing reliance on fish meal and fish oil microbial protein, algal oils, and plant protein (Béné et al., 2016). Reviews and structured syntheses highlight the obstacles still to be overcome while showcasing the potential performance of insects, algae, and microbial substances.

Adopt integrated multi trophic and circular approaches

Integrated multi trophic aquaculture combining fed species with extractive species and broader circular strategies can improve nutrient recycling, diversify farm income and reduce emissions and waste (OECD et al., 2016). Life cycle field studies show IMTA can lower environmental burdens and improve resources efficiency.

Strengthen disease management biosecurity and responsible therapeutics

Disease outbreaks drive large losses and can lead to excessive antibiotic use. Advances in vaccines probiotiocs, genetics, and on farm biosecurity reduce risk and improve welfare. Strengthened surveillance and regionally coordinated emergency response systems are essential as production intensifies.

Emerging species, technologies and systems

Thanks to the current pattern of Asian production, global aquaculture is still dominated by low trophic level species groups such as seaweeds, carps and bivalves (e.g. oysters). These are mainly produced in extensive systems that need relatively simple equipment and limited husbandry. However, there is a growing demand for higher-trophic level species such as sea bass salmonids, some catfish and shrimp from the rapidly expanding middle classes and urbanization, which is likely to result in a move towards more intensive, high technology farming, including recirculating aquaculture systems (Oswald & Mikolasek, 2016). Sustainability is socio ecological expansion must protect livelihoods, indigenous and community rights and promotes gender equity in access to inputs, training and markets. Policies that ignore social dimensions undermine long term viability.

CONCLUSION

Aquaculture methods used nowadays are quite diverse. In terms of the economy, society, and environment, aquaculture must develop sustainably. However, there is no agreement among scientists or operators over which choice or options should be encouraged in order to increase sustainability. However, the aquaculture sector cannot grow to meet the growing demand on the basis of sustainability. Concerned about food security on a national and worldwide scale, national governments and international organizations are supporting sustainable development, increasing aquaculture to boost supply, and investing in innovation to maximize production while addressing environmental and sustainability issues. To overcome these challenges, future research and development should focus on enhancing digital technology, automation and robotics advancement, biosensing for disease detection, integrated multimodal systems, cost-effectiveness, species and environmental adaptability, real-time adaptability, and sustainable energy solutions.

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CHAPTER III

SUSTAINABLE FEEDING STRATEGIES AND ALTERNATIVE PROTEIN SOURCES

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Introduction

Aquaculture has emerged as the fastest-growing food production sector, playing a pivotal role in meeting the global demand for high-quality protein (FAO, 2024). However, its rapid expansion has intensified the reliance on nutritionally balanced and cost-effective feeds, traditionally dominated by fishmeal and soybean meal (Hussain et al., 2024). These conventional protein sources, while nutritionally superior, are increasingly constrained by limited availability, rising costs, and unsustainable production practices. Overfishing, deforestation, greenhouse gas emissions, and competition with human food systems have raised serious concerns about the long-term viability of these ingredients. As the world population is projected to approach 10 billion by 2050, there is unprecedented pressure on aquaculture and livestock industries to secure feed resources that are not only nutritionally adequate but also economically viable and environmentally responsible.

Protein remains the most expensive component of aquafeeds, often accounting for more than half of total production costs. Fishmeal, long considered the "gold standard," offers excellent digestibility and amino acid balance but depends heavily on capture fisheries that are vulnerable to overexploitation and climate variability (Hall, 2010). Similarly, soybean meal, though widely available, carries environmental costs including deforestation, water consumption, and high carbon emissions, in addition to anti-nutritional factors that limit its use at high inclusion levels (Macusi et al., 2023). These challenges underscore the urgency of identifying alternative protein sources that align with the goals of sustainable aquaculture.

Sustainability in fish feeding extends beyond simple ingredient replacement. It integrates ecological, economic, and social dimensions, aiming to reduce dependence on finite natural resources, improve feed efficiency, lower production costs, and ensure consumer acceptance and food safety (Iheanacho et al., 2025). This requires a systemic transformation in feed formulation and management practices. Innovations such as precision feeding, functional feeds enriched with bioactive compounds, and circular economy approaches—where waste streams are converted into feed resources—are reshaping aquaculture nutrition to minimize ecological footprints while maintaining productivity (Akintan et al., 2024).

A diverse range of alternative protein sources is currently under exploration, including plant-derived proteins, animal by-products, microbial biomass, insects, and zooplankton (Dhar et al., 2024). Each of these options presents unique nutritional advantages and sustainability benefits, but also faces limitations related to digestibility, scalability, processing requirements, regulatory acceptance, and cost-effectiveness (Dhar et al., 2024). Their integration into aquafeeds therefore demands careful evaluation of benefits and trade-offs.

This chapter provides a comprehensive overview of sustainable feeding strategies and alternative protein sources for aquaculture. It examines the limitations of conventional ingredients, the potential of various plant- and animal-based alternatives, and the role of microbial and novel proteins in advancing circular and resource-efficient feed systems. Furthermore, it discusses the economic, environmental, and social implications of these strategies while highlighting policy frameworks, processing challenges, and opportunities for future development. By integrating scientific evidence with applied perspectives, this chapter seeks to guide researchers, feed manufacturers, and policymakers toward resilient and sustainable pathways for global aquaculture production.

1. Sustainability in Fish Feeding

Sustainability in animal feeding has emerged as a cornerstone of modern production systems, driven by the urgent need to balance nutritional requirements, economic viability, and environmental stewardship (Figure 1). Feed is the largest input cost and a key factor shaping both productivity and ecological impact, making sustainable feeding strategies essential rather than optional (Albarki et al., 2025).

Nutritionally, the goal is to provide balanced diets that ensure growth and health without excessive reliance on fishmeal and fish oil, whose limited supply and ecological costs demand alternatives such as plant proteins, insect meals, single-cell proteins, and algae-based oils (Hussain et al., 2024). The challenge lies in achieving digestibility, amino acid balance, and nutrient bioavailability while minimizing anti-nutritional effects.

Economically, sustainable feeds must remain affordable and competitive. Though novel ingredients and technologies often involve higher initial costs, they can improve feed conversion, reduce disease, and enhance profitability in the long run (Hossain et al., 2023). Growing consumer demand for eco-labeled seafood further positions sustainability as both a responsibility and a market advantage. Environmentally, sustainable feeding reduces overfeeding, waste discharge, and dependence on wild fish stocks. Precision feeding systems, functional additives, and circular approaches such as reusing by-products improve nutrient efficiency and lessen ecological pressure (Saad et al., 2024). These measures help align aquaculture with global sustainability goals. By integrating nutrition, economics, and environmental care, sustainable fish feeding strengthens aquaculture's role in food security while minimizing its ecological footprint. It represents not just a strategy but the foundation of a responsible and resilient production system.

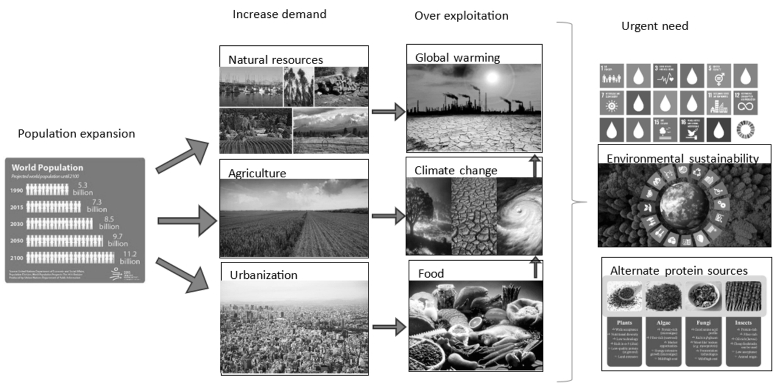

Figure 1. Effect of population expansion on fish demand and need of alternative protein sources. (Created by author, 2025)

2. Fish Meal and Its Demand

Aquaculture, one of the world's largest sectors for animal protein production, is fundamentally dependent on nutrition to sustain growth and productivity. It involves the farming of aquatic organisms under controlled conditions, with feed being the central driver of performance. Fish meal (FM), produced primarily from wild-caught fish, remains the most widely used and costly protein ingredient in aquafeeds. Valued for its high-quality protein and balanced nutrient profile, FM supports the growth and health of farmed fish. However, its use extends beyond aquaculture, as it is also incorporated into feeds for livestock and companion animals. This multi-sectoral demand further reduces the availability of wild fish for direct human consumption. Notably, the production of one ton of FM requires approximately 4–5 tons of whole wild fish (Allan, 2004). Such inefficiency highlights the unsustainability of heavy reliance on FM, and raises concerns about whether aquaculture can expand healthily while continuing to depend on this finite resource as its primary protein source. FM presents several challenges, including the presence of thiaminase, its potential role in transmitting pathogens, and susceptibility to rancidity during storage because of its high lipid content. These issues have intensified research in recent years toward identifying alternative protein sources, such as plant-based, animal-derived, and microbial ingredients. An effective feed formulation relies on high-quality raw materials capable of meeting the nutritional needs of fish, which are largely determined by the amino acid composition of the proteins. Given the high cost of FM and the growing shortage of premium protein sources, there is increasing pressure on the aquaculture sector to transition toward sustainable alternatives. Reliance on FM not only raises economic concerns but also contributes to the overexploitation of wild fish stocks, carrying serious ecological risks.

3. Alternative protein sources to be used in Aquaculture

3.1 Animal Protein Sources

Animal-derived feed ingredients for aquaculture are primarily obtained from the by-products of fish, poultry, swine, and cattle, encompassing various tissues such as blood, intestinal mucosa, feathers, meat, and bone (Jia et al., 2022). These animal by-product meals are regarded as promising alternatives to FM because of their favorable nutritional properties, including amino acid profiles closely resembling those of the target animals, coupled with their relatively low cost. In addition, they offer distinct advantages over plant-based proteins, particularly the absence of anti-nutritional factors (ANFs).

4.1.1. Animal By-Products

Animal by-products include slaughterhouse and meat packaging wastes such as blood, meat scraps, meat and bone meal (MBM), and milk byproducts. These materials are processed into dry powders via rendering, drying, pressing, and de-oiling for use in aquafeeds and monogastric diets (Sharma et al., 2021). They are rich in protein, lipids, vitamins, and minerals, and unlike plant proteins, contain no ANFs, making them strong candidates for FM replacement. However, their digestibility may be reduced by bone, feather, and connective tissues, and bovine spongiform encephalopathy concerns have historically restricted their use, particularly in cattle-derived meals. The EU recently lifted bans on cattle and porcine by-products, increasing their availability for non-ruminant feeds.

4.1.1.1. Meat and Bone Meals

Meat meal and MBM are rendered products from beef, pork, or lamb, excluding blood, hair, hoof, hide trimmings, and stomach contents. Rendered at ~135–140°C in dry cookers, they are sterilized per EU-Directive 90/667/EEC (Hertrampf & Piedad-Pascual, 2000). Meat meal averages ~55% protein and 7–9% fat, while MBM has 45–50% protein, 7–9% fat, and ~33% ash (10–15% higher than meat meal) due to bone content. Amino acid quality is inferior to FM, being lower in lysine, isoleucine, and methionine+cystine.

4.1.1.2. Blood Meal

Slaughterhouse blood, largely discarded except in countries with advanced processing (e.g., Norway), is converted into blood meal via spray-, ring-, or cooker-drying (Li et al., 2008). Spray-drying at ~50°C (vacuum evaporation, followed by 250–300°C drying) yields superior quality compared with ring drying (400–550°C). Blood meal contains >90% protein but is very low in fat (1.2%) and carbohydrate (3.3%) (NRC, 2011). It is deficient in methionine and isoleucine compared with whole egg protein.

4.1.1.3. Milk By-Products

Dairy by-products such as dried whey, skim milk, and casein are occasionally used in aquafeeds. Casein, produced from skimmed milk coagulated with acid or rennet, is the most common, containing ~88% protein and negligible fat (0.7%) (Hertrampf & Piedad-Pascual, 2000). While nutritionally adequate in essential amino acids, casein lacks fat-soluble vitamins and shows variability depending on dairy source. It is mostly used in experimental semi-purified diets rather than commercial feeds.

4.1.2 Fishery Byproducts

Currently, fishery by-products contribute approximately 20% of global FM production. These raw materials, sourced from both capture fisheries and aquaculture, generally consist of trimmings such as blood, viscera, skin, bones, and heads, which are subsequently processed into fish feeds. Fish meal and fish oil remain central components of aquafeeds, particularly for salmonids and marine species derived from pelagic fish. Fish oil is valued for its richness in long-chain omega-3 fatty acids, essential for health, while FM provides high-quality protein with a well-balanced profile of essential amino acids. During processing, about 50–70% of the raw material is classified as "inedible" (Stevens et al., 2018). Nevertheless, FM derived from fishery and aquaculture by-products has been successfully incorporated into aquafeeds. Such by-product FM represents a viable substitute for conventional FM, offering both cost-effectiveness and sustainability as a protein source. For instance, by-product meals derived from species such as tuna and Korean rockfish (*Sebastes schlegeli*) have been effectively used in aquafeeds without compromising fish growth or feed utilization (Jeon et al., 2014; Li & Cho, 2023).

4.1.3 Insects

Insects, being a natural dietary component for many fish species, offer significant promise due to their favorable nutritional properties, low environmental impact, and minimal land requirements (Riddick, 2014). Omnivorous fish consume aquatic insects, while carnivorous fish often feed on insects during juvenile stages before transitioning to fish-based diets. Their nutritional profile, ease of rearing, and high biomass yields make insects strong candidates for partial or complete FM replacement. Seven insect species have been approved for aquafeeds, provided they are grown on feed-grade substrates. Insects contain 50–82% crude protein, depending on species, life stage, and rearing substrate (Makkar et al., 2014). This compares favorably with FM (up to 73%) and soybean meal (up to 50%). Amino acid composition is taxon-dependent: Diptera exhibit amino acid profiles comparable to FM, while Orthoptera and Coleoptera resemble soybean protein but are deficient in lysine and methionine (Barroso et al., 2014). Grasshoppers (*Zonocerus variegatus*) and termites (*Macrotermes bellicosus*) show multiple amino acid deficiencies. In contrast, mosquitoes, honeybees (*Apis mellifera*), mealworms, houseflies, fruit flies (*Drosophila melanogaster*), eri silkworms (*Attacus ricini*), and cockroaches are notable taurine producers (up to

26 mol/g) (Sowa & Keeley, 1996). Lipid content in insects ranges from 8.5–36%, with fatty acid composition largely influenced by diet. Terrestrial insects typically lack highly unsaturated fatty acids (HUFAs), potentially limiting growth and development in fish (Tocher, 2015). However, modifying rearing substrates can improve fatty acid and nutrient profiles. Minerals such as calcium, phosphorus, potassium, zinc, selenium, and iron are also present, though Ca and P levels are usually lower than in FM. Vitamin and mineral composition is strongly dependent on the insect's diet (Makkar et al., 2014).

4.1.4. Poultry by-Products

Poultry by-products, such as feather meal, viscera, skin, crests, and feet, have long been valued as economical and nutrient-rich protein sources, and their use in aquaculture has gained increasing attention as alternatives to FM. Poultry meal, with around 69% crude protein, 10–21% fat, and an amino acid profile comparable to FM, provides high-quality protein and lipids at lower cost, though it generally contains less lysine (Fasakin et al., 2005). Feather meal, containing 80–85% protein and rich in sulfur amino acids, has also been widely tested in both freshwater and marine fish. Poultry byproducts can substitute up to 75% in the diet of juvenile gilthead seabream (*Sparus aurata*) and up to 100% replaced feed of red seabream (*Pagrus major*). Poultry by-products have demonstrated strong potential as partial replacements for FM in aquafeeds across both marine and freshwater species. Studies have shown that up to 50% of FM in the diets of juvenile cobia (*Rachycentron canadum*), gilthead seabream (*Sparus aurata*), and cuneate drum can be effectively substituted with poultry by-products without compromising growth performance (Nengas et al., 1999; Wang et al., 2006; Zhou et al., 2011). Similarly, freshwater species have also responded positively to such inclusion, *i.e.* Sunshine bass (*Morone chrysops* × *M. saxatilis*) exhibited enhanced growth and development when turkey meal completely replaced dietary protein (Muzinic et al., 2006), while gibel carp (*Carassius auratus gibelio*) achieved higher growth rates with a 50% substitution of FM by poultry by-products (Yang et al., 2006). In juvenile tench (*Tinca tinca*), replacing 25% of FM with poultry by-product protein supported good growth performance (González-Rodríguez et al., 2016). Beyond growth, poultry meals have been evaluated for their effects on digestive enzyme activity, a key indicator of protein source suitability, as well as on fillet quality and proximate composition. Processing mechanism of poultary byproducts is illustrated in figure 2.

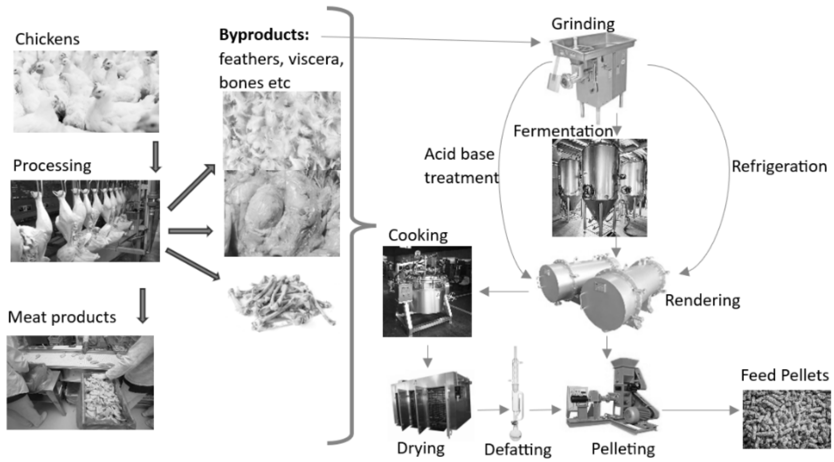

Figure 2. Processing overview of poultry by products into fish feed. (Created by author, 2025)

4.1.5. Microbial Biomass (Single-Cell Proteins)

Microbial biomass, commonly termed *microbial protein* or *single-cell protein (SCP)*, has emerged as a promising alternative for aquafeeds . Among the vast diversity of microorganisms, microalgae, yeasts, and bacteria stand out for their high potential in fish diets. Yeasts and bacteria, in particular, offer high protein content and balanced amino acid profiles, often comparable to FM. Experimental studies have demonstrated that SCPs can effectively serve as feed supplements, supporting growth and health in aquaculture species. Furthermore, nutritional quality can be enhanced by optimizing growth conditions, culture media, and post-harvest processing (Øverland et al., 2013). Several SCP sources are now under active research and commercialization, offering both significant opportunities and challenges for sustainable aquafeed development. The following section outlines the key microbial sources of SCP currently applied in fish nutrition.

4.1.5.1 Fungi

Yeasts and fungi have long been incorporated into animal feeds, primarily for ruminants and, in some cases, direct human consumption. Among the most notable species are *Saccharomyces cerevisiae*, *Fusarium venenatum*, *Aspergillus* spp., *Penicillium* spp., *Rhizopus* spp., *Scytalidium* spp., and *Trichoderma* spp., all of which show strong potential for aquaculture applications. Fungal proteins are rich in methionine, lysine, and B-complex vitamins (Turnbull et al., 1992). For instance, *Kluyveromyces fragilis* can utilize whey as a substrate to produce sulfur-containing amino acids. Compared to algae, fungi typically exhibit a higher nucleic acid content (7–10%). Moreover, fungal oil extracts provide an excellent alternative source of essential fatty acids such as arachidonic acid (ARA), docosahexaenoic acid (DHA), and eicosapentaenoic acid (EPA), which are critical in larval feeding and broodstock diets (Nasseri et al., 2011; Ugalde & Castrillo, 2002).

4.1.5.2 Yeast

Yeasts are single-celled fungi, typically 3–4 µm in size, possessing a cell wall but lacking chloroplasts. They are facultative anaerobes capable of growing with or without oxygen, producing alcohol and CO_2 through sugar metabolism, which also supports their proliferation (Øverland & Skrede, 2016). Yeast and its derivatives have been used in animal feeds for over a century (Shurson 2017). Recently, concerns over antibiotic use in livestock and aquaculture have stimulated interest in yeast-based alternatives that enhance animal health and growth (Shurson, 2017). Fermentation-derived yeast ingredients, such as distillers dried grains with soluble, are now widely incorporated in feeds. Although their potential benefits are well documented, relatively few studies detail their efficiency or species-specific effects, and no adverse impacts on metabolism or aquaculture environments have been reported. Due to their nutritional richness: proteins, lipids, B-vitamins, and minerals—yeasts are increasingly valued in aquaculture feed development. They can also transform low-value agricultural by-products into high-value proteins with minimal land, water, or climate dependency (Agboola et al., 2020). Commercially relevant species include *Saccharomyces cerevisiae*, *Kluyveromyces marxianus*, *Wickerhamomyces anomalus*, *Blastobotrys adeninivorans*, and *Cyberlindnera jadinii*, with crude protein levels of 382–528 g/kg dry matter. Yeasts also contain high ash, moderate carbohydrates, low lipid (mainly unsaturated fatty acids), and essential micronutrients such as B-vitamins, minerals, and enzymes. As protein sources, yeasts provide amino acids beneficial for growth and metabolism. However, imbalances in intrinsic versus crystalline amino acids can affect digestibility. Studies indicate crystalline amino acids are more readily absorbed than intrinsic forms in the intestinal lumen (Larsen et al., 2012). Thus, optimizing yeast inclusion requires balancing amino acid profiles for efficient utilization. Synchronization of both amino acid types with long-term feeding has proven effective in species such as rainbow trout, common carp (Nwanna et al., 2012), Nile tilapia (Lanna et al., 2016), and channel catfish (Salem et al., 2022).

4.1.5.3 Bacteria

Beneficial microorganisms commonly applied in aquaculture include *Bacillus megaterium*, *Bacillus subtilis*, *Streptococcus faecium*, *Streptomyces* spp., *Thermomonospora* spp., and *Lactobacillus* spp. These bacteria have a very short generation time, as their cell populations can double rapidly, often within 20 to 120 minutes. They are capable of utilizing diverse raw materials and edible substrates such as sugars and starches for growth. Bacterial single-cell proteins typically consist of up to 80% protein and provide several essential amino acids. Moreover, bacteria can efficiently proliferate on organic waste and petrochemical by-products like ethanol, methanol, and nitrogen sources. They are also able to grow in nutrient- and mineral-enriched natural waters, which compensates for vitamin deficiencies during cultivation (Sharif et al., 2021).

4.1.5.4 Microalgae

Currently, about 30% of global algae production is used in animal feed. Macroalgae (seaweed) is inexpensive and effective, improving weight gain, triglyceride and protein levels, disease resistance, nitrogen reduction, and digestibility in fish. Combining different algae types enhances growth more than single algae diets. Microalgae like *Chaetoceros*, *Tetraselmis*, *Isochrysis*, and *Nannochloropsis* are commonly used to feed larvae of bivalves, shrimp, and fish, either directly or indirectly through live feed organisms (e*Artemia*, rotifers, *Daphnia*), which transfer essential nutrients to higher trophic levels (Becker, 2013; Liu et al., 2020). Microalgae biomass has 26.5–53.3% protein, with yields higher than soybean protein, making it a suitable aquafeed ingredient. Studies show fish raised on microalgae have better feed conversion ratios than those fed conventional diets. Microalgae are also rich in PUFAs, particularly under stress conditions like freezing, offering better prospects than soybean or peanut-based proteins. Additionally, pigments such as astaxanthin, chlorophyll, and carotene enhance fish growth. However, palatability issues can limit their effectiveness, as higher inclusion levels (0–30%) may reduce body weight, feed intake, and growth rates (Li et al., 2014). Thus, optimizing palatability is essential for sustainable microalgae-based aquaculture feeds.

4.1.6. Tubifex

Tubifex tubifex (Annelida: Tubificidae) is a commonly used live bait in ornamental fish culture owing to its convenient size and wide availability. It is considered highly nutritious, being rich in n-3 fatty acids (e.g., C18:3n-3 and C20:5n-3) as well as n-6 fatty acids (C18:2n-6 and C20:4n-6), and it maintains a relatively stable nutrient composition. Previous studies have highlighted its high levels of protein, lipids, and essential fatty acids, in addition to its strong palatability. Supplementation with *Tubifex* has been shown to enhance growth performance and survival in *Pseudoplatystoma fasciatum* (Arslan et al., 2009). Members of Tubificidae, particularly *T. tubifex* (Müller), have also been employed in the rearing of the freshwater shrimp *Macrobrachium lanchesteri* (De Man) (Panikkar et al., 2010). Furthermore, feeding trials have demonstrated that *Tubifex* can significantly promote growth in ornamental fishes such as *Chitala chitala*, *Poecilia reticulata*, and *Betta splendens* (Görelşahin et al., 2018; Sarkar et al., 2006).

4.1.7. Shrimp and Crab Meal

Commercial shrimp feeds typically contain 30–50% crude protein, whereas FM generally offers higher protein levels and a more favorable nutritional profile, making it a highly desirable component in animal diets. Shrimp waste meal, derived from processing residues, represents a valuable animal protein source enriched with lysine and chitin, both of which contribute important nutritional benefits. Its composition ranges from 35–55% protein and 13–38% ash, highlighting its potential as a functional ingredient in aquafeeds. Similarly, red crab meal has historically been utilized in aquaculture, primarily as a pigment source. Red crabs are rich in carotenoids, particularly astaxanthin, the predominant pigment (Spinelli & Mahnken, 1978). Diets supplemented with red crab meal have been used to enhance pigmentation in salmonids and incorporated into formulated feeds for shrimp and American lobsters, underscoring its dual role as both a nutritional and functional feed ingredient.

4.1.8. Krill Meal

Antarctic krill (*Euphausia superba*), a shrimp-like crustacean abundant in the Antarctic Ocean, plays a central role in the marine food web and has attracted attention as a valuable feed ingredient (Nicol & Endo, 1999). Krill meal, produced from boiled and dried whole krill, yields a brownish-orange powder with a stable amino acid profile. It is rich in protein and lipids (5–14%), providing unsaturated fatty acids such as EPA and DHA, predominantly bound in phospholipids, which enhances tissue absorption compared to triglyceride-bound omega-3s. Krill also contains carotenoids, notably astaxanthin, along with chitin, trimethylamine oxide, free amino acids, and nucleotides that act as feeding stimulants (Burri & Nunes, 2016). Krill oil and meal are the two major products; krill oil exhibits higher EPA and DHA levels than fish oil, while krill meal provides protein, phospholipids, choline, and feed attractants in one package. Despite the high ash and fluoride from its chitinous exoskeleton, studies show fluoride does not accumulate in fish tissues. Inclusion of krill meal in aquafeeds enhances protein intake, growth, feed efficiency, pigmentation, and flesh quality, while counteracting feeding depression in high plant-based diets or under stress conditions.

Astaxanthin further contributes to pigmentation and exhibits antioxidant and anti-inflammatory properties by scavenging free radicals and reducing oxidative damage (Graf et al., 2010). These combined nutritional and functional benefits make krill meal particularly valuable in shrimp and fish diets, improving growth, survival, stress resistance, and overall product quality.

4.1.9. Zooplanktons

Zooplankton plays a vital role in transferring energy from primary producers to higher trophic levels. They serve as starter feed for most fish larvae and many planktivorous adults, with their abundance directly influencing pelagic fisheries and ecosystem stability. In aquaculture, zooplankton is especially valuable for fry and finfishes, as larval stages depend on them once the yolk sac is absorbed. Larger aquatic animals such as whales also consume plankton, highlighting its ecological significance. In tropical waters, the high metabolic rate of young fish further increases the importance of zooplankton as a dietary source. Zooplankton are often described as "living capsules of nutrition," providing proteins, essential amino acids, lipids, fatty acids, sterols, pigments, and vitamins. Studies across regions confirm their role as sources of key fatty acids, amino acids, and antioxidants crucial for larval growth and survival (Boechat & Giani, 2008; Hamre, 2016).

4.1.9.1 Artemia

Artemia, commonly called brine shrimp, is among the most widely used live feeds in hatcheries, particularly *A. salina* and *A. franciscana* (Aragão et al., 2004; Kadhar et al., 2014). Artemia nauplii are convenient feed but are nutritionally deficient in essential fatty acids (Navarro et al., 1992). Enrichment with HUFAs, particularly EPA and DHA, improves larval growth and survival (Smith et al., 2002).

4.1.9.2 Rotifers

Rotifers are regarded as superior starter feeds due to their nutritional quality, small size, and ability to deliver proteins, vitamins, and micronutrients to fish larvae. Their tolerance to varied salinity and temperature, high reproductive rates, and ease of mass culture make them the most preferred live feed in hatcheries. Marine species such as *Brachionus plicatilis* are widely used in finfish and shrimp culture, while freshwater species like *B. calyciflorus* and *B. rubens* show potential though limited use (Mills et al., 2016). Batch culture remains the dominant production method (Dhert et al., 2001).

4.1.9.3 Copepods

Copepods, the most diverse Crustacea group with ~6000 species, occur in both marine and freshwater habitats and are often considered superior to Artemia and rotifers. They provide high levels of proteins, vitamins, carotenoids, and essential fatty acids such as EPA, DHA, and ARA, which enhance growth and reduce deformities in larvae (Conceição et al., 2010; Matsumoto et al., 2009). They also supply antioxidants like astaxanthin and vitamins C and E, protecting HUFAs from peroxidation (Drillet et al., 2011; McKinnon et al., 2003). However, large-scale culture remains challenging due to their limited adaptability, restricting their use mainly to hatcheries.

4.1.9.4 Cladocerans

Cladocerans, commonly known as “water fleas,” such as *Daphnia* and *Moina*, are important live feeds in freshwater aquaculture due to high reproduction rates, adaptability, and nutritional quality. They provide essential amino acids, fatty acids, and proteins needed for larval development (Qin & Culver, 1996). Species like *Diaphanosoma birgei* and *Moina micrura* are also cultured as reliable feed for finfish larvae and fingerlings (SipaÚBa-Tavares & Bachion, 2002). Their short life span and rapid embryonic development allow for efficient large-scale culture.

4.1.9.5 Fairy Shrimps

Fairy shrimps are freshwater microcrustaceans found in pools and artificial habitats worldwide. They are cost-effective, highly digestible, and nutritionally comparable to Artemia, containing proteins, essential amino acids, fatty acids, and carotenoids such as astaxanthin and canthaxanthin (Dararat et al., 2012). Their rapid growth, large biomass, and minimal impact on water quality make them a promising alternative live feed in both freshwater and marine hatcheries.

4.2. Plant protein sources

Plant protein sources are considered the primary alternatives to FM, because of their availability, lower cost, and diverse amino acid profiles (Abdul Kari et al., 2023). Commonly used ingredients include cereal grains (wheat, corn), oilseeds (soybean, sunflower, rapeseed, cottonseed), and pulses (beans, lupins, peas) (Burducea et al., 2022; Kaiser et al., 2022; Obirikorang et al., 2020; Ogello et al., 2017; Rema et al., 2019; Szczepański et al., 2022). However, their use is constrained by ANFs, such as phytate, trypsin inhibitors, and lectins, that reduce palatability, impair nutrient utilization, and may induce inflammation (Aragão et al., 2022). In addition, carbohydrate fractions in plant proteins can negatively affect digestion and absorption (Dossou et al., 2021). Findings on FM replacement with plant proteins remain inconsistent. Some studies report reduced feed intake (FI) and growth at high inclusion levels (Kari et al., 2022; Sharawy et al., 2016), whereas others indicate no negative effects (Valente et al., 2016) or even growth improvements (Abdul Kari et al., 2023). These mixed results suggest that combining multiple plant protein sources may better fulfil the nutritional requirements of aquaculture species.

4.2.1 Soybean and soybean by-products

Soybean (*Glycine max* L.) from the Leguminosae family is the most widely used plant protein source replacing FM in aquafeeds (Dei, 2011). Soybean meal (SBM) provides a balanced amino acid (AA) profile, particularly rich in lysine, tryptophan, threonine, and isoleucine, often limited in cereal grains (Florou-Paneri et al., 2014). Soybean by-products (fermented SBM, soy pulp, soy protein concentrate) are also valuable alternatives, as fermentation reduces ANFs, such as tannins, phytates, and phenols, while enhancing antioxidant compound bioavailability (Abdul Kari et al., 2023; Zhang et al., 2023; Zulhisyam et al., 2020). In African catfish (*Clarias gariepinus*), 50% fermented soy pulp (FSP) improved growth and reduced FCR due to lactic acid fermentation enhancing nutrient value and eliminating allergens (Kari et al., 2022). Similar improvements were observed in Japanese seabass with >80% inclusion (Rahimnejad et al., 2019). Fermented soybean by-products have also been linked to better immunity, stress response, gut morphology, fillet quality, and biochemical indices (Zhang et al., 2021). For instance, partial FM replacement increased lysozyme activity, total antioxidant capacity, SOD, and CAT activity while reducing intestinal pro-inflammatory cytokines (IL-1β, IL-6, TNF-α), and upregulating genes linked to growth and immunity (TGF-β1, NF-kβ, hsp90α) (Kari et al., 2022; Zhang et al., 2021). Blood biochemistry also reflects these improvements.

In stinging catfish (*Heteropneustes fossilis*), 75% SBM increased glucose and body weight due to higher hemoglobin levels and oxygen transport, while gut villi length, area, and thickness improved up to 50% SBM inclusion before declining at 75% (Howlader et al., 2023). FSP similarly improved gut morphology in African catfish, maintaining intact epithelial barriers and goblet cell organization (Kari et al., 2021). However, excessive SBM can cause health issues. Salmonids, turbot, yellowtail, northern snakehead, and seabass exhibited gut disturbances with >10% SBM, largely due to residual ANFs (Liu et al., 2019; Miao et al., 2018; Nimalan et al., 2022; Viana et al., 2019; Zhang et al., 2018). Liver functionality may also be affected: *Sparidentex hasta* juveniles fed high SBM or soy protein showed elevated alkaline phosphatase, while largemouth bass (*Micropterus salmoides*) had improved ALT and AST levels when fermented soybean replaced 20–60 g/kg SBM (Jiang et al., 2018; Yaghoubi et al., 2016).

4.2.2. Corn/wheat gluten meal

Corn gluten meal (CGM), a corn starch by-product from wet milling, contains 67–71% protein, low fiber, and lacks ANFs, though it is deficient in Lysin and Trptophan (Kopparapu et al., 2022). Processing can improve its solubility and digestibility, enhancing its feed applications (Huang et al., 2024). Wheat gluten meal (WGM), with ~75% protein, low Lysin, and high digestibility, is also used in aquafeeds, especially salmonids, allowing FM replacement up to 35% without adverse effects (Bonaldo et al., 2015; Storebakken et al., 2000). In olive flounder (*Paralichthys olivaceus*), replacing FM up to 30% with CGM and fermented SBM maintained growth, feed use, and immunity (Seong et al., 2018). However, >80% FM replacement with CGM reduced growth and feed efficiency in juvenile spotted rose snapper (*Lutjanus guttatus*) (Hernández et al., 2021). Increasing CGM levels also lowered Hb and hematocrit while raising triacylglycerides, linked to upregulation of lipogenic genes (Song et al., 2018). In Atlantic salmon, 30% WGM induced gluten sensitivity-like symptoms, associated with upregulation of cholecystokinin genes affecting feed intake and intestinal metabolism (Johny et al., 2020).

4.2.3. Canola and rapeseed by-products

Rapeseed (*Brassica napus* L.), also known as canola, ranks fifth among oil crops and is mainly cultivated for oil extraction, leaving a protein-rich meal (36–50%) (Kaiser et al., 2022). Rapeseed meal (RM) is the second most produced oilseed meal after SBM (Carré & Pouzet, 2014), widely used in cattle, poultry, and aquaculture. However, ANFs such as glucosinolates, erucic acid, tannins, and phytic acid limit its dietary inclusion to 10–20% (Sallam et al., 2021). Processing methods have improved protein content and reduced ANFs, enabling up to 66% FM replacement in rainbow trout diets without growth loss (Kaiser et al., 2021). In red sea bream, fermented RM replacing FM (25–100%) enhanced growth and antioxidant defense, with best results at 25% inclusion (Dossou et al., 2018).

4.2.4. Lupin (*Lupinus* L.)

The genus *Lupinus* (Fabaceae) includes over 260 species, but only four are cultivated: white (*L. albus*), blue (*L. angustifolius*), yellow (*L. luteus*), and pearl (*L. mutabilis*). Low palatability and ANFs (non-starch polysaccharides, fibers, oligosaccharides) limit its use (Struti et al., 2020). Dehulling increases protein content (31–54% DM) and improves nutritional value (de Vries et al., 2012). Lupin seeds are rich in Leucin, Valine, Threonine, isoleucine, and Serine but deficient in Trptophan and sulfur AAs (Sujak et al., 2006). In aquaculture, high FM replacement with lupin meal (51% in barramundi, 21% in cobia) caused liver steatosis, kidney necrosis, and gut damage (Pham et al., 2020). However, species like common carp showed no adverse effects when white or blue lupin were included (Anwar et al., 2020).

4.2.5. Faba bean (*Vicia faba* L.)

Faba bean (FB) seeds are rich in protein (25–33% DM) and starch (40–48% DM), making them valuable for food and feed. However, ANFs like vicine and convicine cause favism (Rizzello et al., 2016). In Nile tilapia, FB inclusion (40–70%) reduced body weight proportionally (Li et al., 2023). In grass carp, FB replaced SBM up to 420 g/kg without affecting growth, but higher inclusion (560 g/kg) impaired performance (Gan et al., 2017).

4.2.6. Pea (*Pisum sativum* L.)

Pea, a legume of the Fabaceae, contains 18–33% protein, with lower digestibility and sulfur AA content than soybeans, but fewer ANFs (Walter et al., 2022). However, higher levels of Leucine, Serine, and Threonine contribute to off-flavors (Fischer et al., 2020). Pea products, including pods (food waste) and protein concentrate, are used as FM alternatives. In common carp, 20% pea pod powder improved growth and FCR (Tewari et al., 2019). FM replacement with pea protein concentrate (25–50%) supported growth in rainbow trout, lumpfish, and tench (Demirci et al., 2021; Willora et al., 2020). However, higher inclusions caused liver histopathology in trout and reduced growth in tench (Demirci et al., 2021).

4.2.7.1. Sunflower meal (SFM)

Sunflower meal (290–340 g/kg protein) is an inexpensive by-product with good palatability, used as a protein source for fish (Shi et al., 2023). Although lower in sulfur AAs than SBM, it is rich in glutathione and aspartic acid. Partial substitution of SBM with up to 30% SFM improved tilapia growth and feed efficiency (Christopher et al., 2020). In turbot, 12.9% SFM replaced FM without adverse effects, improving antioxidant status (Zhou et al., 2016). Conversely, higher inclusions (>25% FM or >50% SBM replacement) reduced growth in tilapia and grass carp due to AA imbalance and high fiber (Ogello et al., 2017; Shi et al., 2023). Incomplete decortication and high lignin content further limit its use at high levels.

4.2.7.2. Cottonseed meal (CSM)

Cottonseed meal (23–53% protein) is cheaper and palatable but limited by AA imbalance and ANFs like gossypol. In *Catla catla*, up to 50% SBM replacement with CSM supported growth and antioxidant indices, but higher inclusion impaired enzyme activity and gut morphology (Aslam et al., 2023). In red drum, CSM could replace 50% FM protein without affecting growth or body composition, but higher levels reduced feed efficiency (Wang et al., 2020). Interestingly, red drum showed lower sensitivity to ANFs than other carnivores (Minjarez-Osorio et al., 2016). In Russian sturgeon, CSM outperformed SBM, improving final BW and SGR with no adverse serum effects (Emre et al., 2018).

4.2.7.3. Linseed protein concentrate (LPC) and oil cake (LOC)

Linseed meal (≈300 g/kg protein) has limited use due to high fibre. LPC, with reduced ANFs, can replace FM up to 400 g/kg in silver catfish diets without affecting growth or metabolism. Similarly, deoiled linseed oil cake (34% CP) tested in rohu diets showed that fermented LOC replaced 30% FM effectively, improving growth, protein efficiency, carcass protein, and digestive enzyme activity compared to raw LOC (Banerjee et al., 2023). Fermentation improved nutrient bioavailability and reduced ANFs, making LOC a cost-effective FM alternative.

4.2.7.4. Pumpkin seed cake (PSC)

Pumpkin seed cake (PSC), rich in protein, fiber, and minerals, is a promising SBM/FM replacer. In tilapia, PSC supplementation (33–134 g/kg) improved weight gain, FCR, antioxidant capacity, and immunity, while lowering serum cholesterol, triglycerides, and liver enzymes (Mounes et al., 2024). Similar benefits were found in mirror carp, where PSC reduced cholesterol and improved growth at moderate levels (Sezgin & Aydın, 2021). Pumpkin seed meal (2–6 g/kg) enhanced tilapia feed efficiency, immunity, and resistance to *Aeromonas hydrophila* (Musthafa et al., 2017). In shrimp, pumpkin pomace improved FCR, protein, carotenoid content, and body color, whereas seeds reduced growth and antioxidant activity (Zancan et al., 2023).

5. Benefits and Challenges of Alternative Protein Sources for Aquaculture

5.1 Economic Viability

Alternative protein sources for aquaculture must be assessed for both sustainability and cost. Fishmeal, though nutritionally superior, is expensive and unsustainable in the long term (OECD-FAO, 2023). Plant proteins, especially soybean meal, are the most widely used due to low price, availability, and established supply chains. Animal by-products and fishery wastes are also cost-effective and support circular economy models. In contrast, novel proteins such as insect, microbial, and algae meals remain limited by high processing costs and lack of large-scale production, despite their sustainability potential. Future cost reductions through economies of scale, co-product valorization, and supportive policies are essential for their economic viability (Wachira et al., 2021).

5.2 Availability of Alternative Proteins and Social Conflicts

Despite global availability, utilization is constrained by weak technology, seasonal variability, climate change, and poor reporting systems (Munguti et al., 2021). Microbial protein is limited to a few countries due to lack of expertise, while animal by-products remain underused commercially due to inadequate facilities.

5.3 Sustainability

Shifting to sustainable proteins is essential as feed drives aquaculture's emissions. Terrestrial animal proteins generate higher GHGs than FM, but by-products reduce additional impacts (Tanga & Kababu, 2023). Insects and microbial proteins require fewer resources, while LCAs show mixed outcomes for FM versus soy, rapeseed, and blood meal. Valorizing wastes, such as BSF conversion of organic matter, supports circular bioeconomy models (Verner et al., 2021).

5.4 Feed Security and Safety Concerns

FM carries risks of heavy metals, hydrocarbons, and microplastics (Habib et al., 2022; Iheanacho et al., 2023). Plant proteins may contain pesticides and mycotoxins, while animal by-products risk bacterial and chemical residues. Stronger sourcing, advanced processing, and tighter regulations are needed (Glencross et al., 2019).

5.5 Anti-Nutrients

Plant proteins contain ANFs (e.g., saponins, tannins, phytates, lectins, glucosinolates) that impair digestibility and absorption (Prabu et al., 2017). Animal by-products may contain ash or chitin, both requiring processing to improve bioavailability.

5.6. Shortfall in Processing Infrastructure

Adoption is limited by obsolete technologies, high energy costs, and lack of modern facilities (Adeleke et al., 2020). Advanced processing and renewable energy use are needed to expand availability.

5.7 Policy Regulations

Weak, inconsistent, and bureaucratic policies restrict investment and growth in alternative protein industries (Tanga & Kababu, 2023). Poor documentation further limits regulation and planning.

5.8 Socioeconomic Impacts

Alternative proteins can enhance food security and create jobs across the value chain (Talwar et al., 2024), benefiting smallholders, women, and youth through local supply chains.

5.9 Social Acceptance of Alternative Proteins

Cultural, social, and religious concerns, along with skepticism toward GM proteins, limit acceptance (Siddiqui et al., 2022). Awareness campaigns and trust-building are needed.

6 Solutions and Recommendations

Despite being theoretically available and cheaper, alternative proteins remain underutilized due to policy gaps, high costs, and weak infrastructure. Progress requires evidence-based policies, R&D funding, advanced processing (e.g., fermentation, enzymatic hydrolysis), renewable energy adoption, and awareness campaigns to foster acceptance. Combined reforms could unlock economic, environmental, and food security benefits.

7. Conclusion

Sustainable feeding strategies and alternative proteins are essential for the future of aquaculture, as reliance on fishmeal is increasingly unsustainable and costly. Options such as animal by-products, plant proteins, insects, and microbial sources can partially replace fishmeal while supporting nutrition and efficiency. However, challenges including safety, anti-nutritional factors, infrastructure, policies, and social acceptance must be addressed, as many novel proteins remain less cost-competitive. Despite these hurdles, benefits such as reduced pressure on wild fish stocks, waste valorization, and alignment with circular bioeconomy principles make this transition critical. Advancing research, improving processing, strengthening policies, and raising awareness will be key to building resilient, sustainable, and socially responsible aquafeed systems that secure future food and nutrition needs.

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CHAPTER IV

NUTRIENT MANAGEMENT AND WASTE REDUCTION IN AQUACULTURE

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Introduction

Aquaculture is one of the fastest-growing food-producing sectors, expanding at an average annual rate of 3.2% and playing a crucial role in ensuring global food security by meeting the nutritional needs of a growing human population (Tom et al., 2021). According to Food and Agriculture Organization (2020), aquaculture supplied more than half of all fish consumed worldwide in 2020 and this share is projected to increase further at 60% by 2030. However, the rapid expansion of aquaculture has led to sector intensification, where rearing fish at high densities generates considerable amounts of effluents (Henares et al., 2020), raising concerns about nutrient discharge and waste accumulation in culture systems and surrounding environments. Moreover, in fish, molluscs, and crustaceans, only one-third of the feed nutrients are digested, absorbed, and utilized in the metabolic process, while the remaining two-thirds of the feed nutrients are discharged as fecal waste and dissolved nutrient waste (Meriac et al., 2014).

Feed-based aquaculture systems generate a substantial amount of waste per unit of production, with estimated discharges ranging from 323-514 kg carbon, 6.1-15.9 kg phosphorus and 35.9-63.5 kg nitrogen per ton of fish produced (Chatvijitkul et al., 2017). Moreover, in China, nutrient loads from aquaculture increased from 1.0 to 1.6 million tonnes of nitrogen and 0.1 to 0.2 million tonnes of phosphorus between 2006 and 2017 (Wang et al., 2019). Additionally, the annual discharge of nitrogen and phosphorus was 27.0kg/h and 9.0kg/h in Norwegian fish farms, respectively (Hamilton et al., 2016). In Japan, the discharged rate of organic matter ranges from 3.9 to 11.7mg/day (Srithongouthai et al., 2017). Furthermore, according to Neto and Ostensky (2015), each ton of tilapia produced releases approximately 1,040 kg of organic matter, 45 kg of nitrogen, and 14 kg of phosphorus into the environment. Thus, the amount of waste depends upon the species being farmed, stocking density, management practices, production system, and the quality of the feed.

Effluents from aquaculture systems contain uneaten feed, fecal matter, particulate organic matter, and metabolic by-products, such as ammonium, phosphorus, and dissolved organic carbon (Crab et al., 2007) and are categorized into solid and dissolved wastes. Solid wastes primarily consist of fecal matter, uneaten feed particles, and dead fishes (Chiquito-Contreras et al., 2022). Moreover, dissolved wastes, mainly phosphorus and nitrogen which are byproducts of fish metabolism and excretion, are partially retained by fish and excess is released into the culture water (Dauda et al., 2019). These discharged solids and dissolved wastes deteriorate water quality, contribute to ammonia toxicity, cause oxygen depletion, eutrophication, and harmful algal blooms in receiving environments (Tabrett et al., 2024).

To reduce environmental impacts and ensure the long-term sustainability of aquaculture, there is a dire need to implement effective and stringent waste management strategies (Bureau & Hua, 2010). Strategies such as optimizing feed formulation, adopting a recirculating aquaculture system (RAS), integrating species through integrated multi-trophic aquaculture (IMTA), and installing mechanical and biological filters are increasingly used to reduce nutrient loading and improve water quality (Olsen et al., 2008). Since feed is the main source of waste in aquaculture, effective nutritional management by optimizing feed formulation is necessary (Cho & Bureau, 2001).

This chapter summarizes the dietary sources of aquaculture wastes and their nutritional management strategies to minimize the concentration of these wastes and prevent their adverse effects on aquatic ecosystem.

Dietary waste sources and its impact on environment

Feed constitutes a major role in aquaculture production and its significance varies with the culture technique employed (Dauda et al., 2017). In intensive aquaculture, the transformation of dietary nutrients into fish biomass are intrinsically incomplete, generating nutrient rich wastes that are often challenging to manage and recycle. Therefore, feed has been recognized as the main contributor to the waste production in aquaculture environments (Akinwole et al., 2016). The feed utilization efficiency and resultant waste production depends on multiple factors including manufacturing process, nutrient composition, storage period, feeding strategy and pellet size relative to fish size (Miller & Semmens, 2002). These wastes may induce environmental modifications with their nature and severity largely dependent on the intrinsic properties of the recipient ecosystem. In general, aquaculture waste is categorized into solid waste (undigested feed) and dissolved waste (metabolic by-products) (Piedrahita, 2003). A basic understanding of these wastes-related issues is essential for the development of effective mitigation strategies.

Solid wastes

Solid wastes also known as particulate organic matter generally account for the predominant fraction of total waste generated in aquaculture operations, derived primarily from residual feed and fecal matter of cultured animals (Akinwole et al., 2016). Dietary nutrients are digested and then absorbed while indigestible compounds along with the endogenous material, such as digestive enzymes, microbial residues and sloughed off cells, are egested as feaces. In properly regulated aquaculture system, almost 30% of the feed is lost in the form of solid waste (Miller & Semmens, 2002). Solid wastes can be categorized into settled solids, which sink rapidly, and suspended solids, which remain floating in water for an extended period. Settled particles are relatively large and can be removed with ease (Ebeling & Timmons, 2012), whereas suspended particles are much finer and constitute the most challenging fraction to eliminate from culture system (Cripps & Bergheim, 2000). Solid wastes have been identified as the most deleterious waste in aquaculture system, highlighting the need for their effective and immediate removal to prevent adverse effects. If solid wastes persist in the system for a long time and begin to decompose, they release the phosphorous and nitrogenous compounds, stimulating algal growth and promoting eutrophication (Bureau & Hua, 2010), which induces stress for cultured fish and may clog their gills, leading to the death. Moreover, the microbial degradation of sedimented solids utilizes oxygen and produces carbon dioxide and ammonia, thereby reducing dissolved oxygen (Timmons & Losordo, 1994). This oxygen depletion can stimulate hydrogen sulphide formation, which exerts toxic effects on aquatic animals and disrupt the ecosystem balance. The elevated levels of hydrogen sulphide and ammonia and reduced dissolved oxygen can also cause damage to the benthic community (Magni et al., 2008). On the other hand, suspended solids may block the penetration of light in water, hindering the photosynthetic process of phytoplankton, thereby reducing their survival and results in their mortality (King et al., 2021).

Dissolved wastes

Dissolved wastes are nutrient by-products released into the aquatic environment through nutrient metabolism in fish or decomposition of uneaten feed. Nitrogen and phosphorus compounds are two primary constituents of dissolved wastes, comprising key components of protein, which is the main constituent of fish feed (Boyd & Massaut, 1999; Piedrahita, 2003). Protein-rich diets have elevated levels of nitrogen and phosphorus but less than 50% of these nutrients are retained in the fish body while the remainder is excreted, leading to reduced water quality (Piedrahita, 2003). Dissolved wastes are therefore broadly classified into nitrogenous wastes and phosphorus wastes, each exerting adverse effects on aquatic ecosystems.

Nitrogenous wastes

Nitrogenous waste represents one of the most significant forms of dissolved waste, originating from protein catabolism in fish and decomposition of residual feed. Its production is mainly influenced by factors that regulate the breakdown and retention of amino acids by fish. Fish assimilate only a limited portion of nitrogen, while the excess is excreted into the aquatic environment, contributing to aquatic pollution (Lazzari & Baldisserotto, 2008). Excreted nitrogen enters the water as ammonia, which may be further oxidized into nitrite and nitrate through microbial activity. Ammonia is a primary excretory product, existing in un-ionized form (NH_3) which is highly toxic and the ionized form (NH_4^+) which is much less toxic. To avoid toxicity, concentration of ammonia below 1 mg/L is generally recommended. Nitrite (NO_2^-) is produced as an intermediate during the oxidation of ammonia to nitrate (Ajani et al., 2011). Although it is unstable and further transformed into nitrate, it can still induce toxic effects in aquatic organisms by interfering with the oxygen-carrying capacity of hemoglobin in fish or hemocyanin in crustaceans (Camargo & Alonso, 2006). Therefore, the concentration of nitrite below 0.5 mg/L is generally recommended in aquaculture to prevent toxic effects (Ajani et al., 2011). Nitrate (NO_3^-) is the final product of ammonia oxidation and is generally considered safe for most fish species even at high concentrations up to 200 mg/L.

Collectively, high concentrations of these nitrogen ions (NH_4^+, NO_2^- and NO_3^-) promote the growth and proliferation of primary producers (phytoplankton, macrophytes and benthic algae), leading to eutrophication of aquatic environments. In severe cases, harmful algal blooms (dinoflagellates, diatoms and cyanobacteria) are stimulated, releasing toxins into the surrounding water. These toxins affect aquatic organisms directly through absorption, ingestion or contaminated drinking water and indirectly through bioaccumulation and biomagnification in the food web (Camargo & Alonso, 2006).

Phosphorus wastes

Phosphorus is supplied as an essential element in aquaculture feed however, its availability to cultured animals is generally limited. Consequently, in intensive aquaculture systems, a considerable proportion of dietary phosphorus is excreted and released into the surrounding water (Dauda et al., 2019).Thus, feed serves as a main contributor of phosphorus waste in aquaculture, with losses occurring both in particulate form through feces and uneaten feed or in dissolved form via excretion. Contrary to nitrogenous wastes, phosphorus wastes do not directly induce toxic effects on cultured animals however, its release into the aquatic environment leads to accumulation in receiving water bodies (Wong, 2001). In freshwater ecosystems, phosphorus serves as the primary limiting nutrient for algal growth. Elevated phosphorus accelerates eutrophication by stimulating rapid growth of primary producers, whose subsequent degradation lowers dissolved oxygen in bottom waters with limited circulation (Bureau & Hua, 2010). The severity of this process depends on the amount and rate of release as well as the carrying capacity of the water body, consequently threatening aquatic organisms and disrupting the ecological balance of aquatic communities (Wong, 2001).

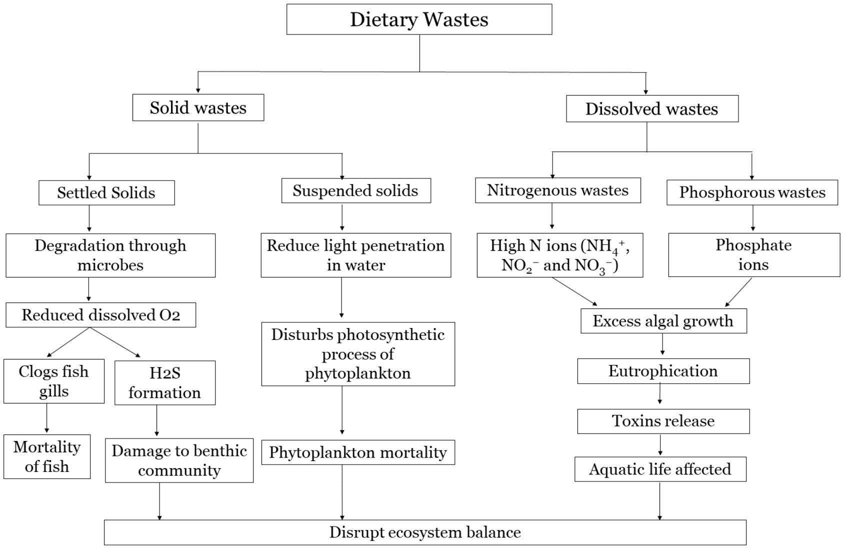

Figure 1. Impacts of aquaculture dietary wastes on aquatic life and ecosystem balance. In aquaculture systems, solid and dissolved wastes contribute to oxygen deficiency, light reduction, eutrophication and toxin release leading to adverse effects on aquatic organisms and disrupt ecosystem stability (Created by the authors, 2025).

Reducing waste output through nutritional strategies

Most of the aquaculture wastes originate directly from the feed, making diet formulation and feeding practices the most practical and effective way to reduce waste in aquaculture. Along with other biological and environmental factors (Reid et al., 2009), diet digestibility, nutrient density (Cho & Bureau, 1997) and protein-energy balance (Kaushik, 1994) in the diet largely affect waste outputs by animals. Physical waste treatments such as biofiltration, recirculating aquaculture systems and biofloc technology capture or process wastes after they are discharged, which is often costly and energy intensive. However, nutritional strategies involve optimizing nutrient balance, improving their digestibility and preventing overfeeding, ultimately reduce waste generation at the source. In this way, they not only minimize environmental impacts while also improve feed efficiency which make them ecologically and economically sustainable for waste management in aquaculture (Bureau & Hua, 2010; Cho & Bureau, 2001).

Nutritional strategies to reduce solid waste output

Improving ingredient digestibility and quality

Digestibility and quality of feed ingredients are the main factors that influence solid waste production in aquaculture. Low quality and poorly digestible ingredients such as grain by-products or high fiber ingredients contribute to larger outputs. Whereas, highly digestible ingredients with high protein and lipid content lead to more efficient nutrient retention and less waste output. Therefore, exclusion of indigestible ingredients during feed formulation can be a preventive nutritional strategy for waste reduction (Cho & Bureau, 2001).

Improving feed efficiency through high nutrient density diets

Use of high-nutrient-density (HND) diets provides more digestible nutrients per unit weight of feed compared to regular grower diets. HND diets improve feed efficiency by allowing fish to meet their nutritional requirements with a lower feed intake, ultimately reduce solid waste output (Cho et al., 1994). For example, adoption of HND extruded feeds has reduced solid waste discharge by around half per tonne of fish biomass nowadays (Bureau & Hua, 2010).

Processing of ingredients

In addition to the selection of high-quality feed ingredients, their processing also plays critical role in enhancing nutrient availability and reducing solid waste discharge. Processing strategies such as dehulling, solvent extraction and enzymatic treatments reduce indigestible fractions in plant-based ingredients. Similarly, processing strategies for animal by-product meals such as thermal heat, elutriation and air classification reduce ash, starch and non-starch polysaccharides contents from them and facilitate retention of greater portion of nutrients in fish body by maximizing their digestibility rather than being lost as waste (Bureau & Hua, 2010).

Feed manufacturing technologies

Techniques used for feed manufacturing also affect nutrient utilization and waste generation. Traditional steam-pelleted feeds are usually less stable in water and have low digestibility, leading to more nutrient losses via uneaten feed and feaces. However, modern feed manufacturing technologies such as extrusion increase starch gelatinization and improve pellet durability, resulting in more nutrient-rich diets with less waste output (Bureau & Hua, 2010).

Minimizing waste output through feeding strategies

Feeding fish beyond their nutritional requirements is also a source of solid waste discharge which can be prevented by improving feeding practices. Practical feeding strategies including accurate feed rationing and controlled feeding regimes with optimized frequency which not only reduce uneaten feed but also optimize feed utilization. Thus, by adjusting feed delivery according to the fish needs, solid waste output can be minimized (Cho & Bureau, 2001).

Nutritional strategies for reducing Phosphorus waste output

Formulation of feed based on digestible phosphorus

Improving the digestibility of phosphorus in fish feed is essential for limiting nutrient losses and lowering the risk of eutrophication. Phytate bound phosphorus from plant sources have a very low digestibility of less than 10%. Mineral phosphate like dicalcium phosphate are moderately to highly digestible (60-95%), whereas bone phosphorus in hydroxyapatite form is less digestible (40-60%). Using ingredients rich in easily digestible P and avoiding poorly digestible sources can help lower P waste and enhance nutrient absorption in fish (Hua & Bureau, 2006).

Use of exogenous phytase to improve Phosphorus utilization

In aquaculture, exogenous phytase is generally obtained from microbial and fungal sources and is usually added to fish feed to increase the digestibility of phytate-bound phophorus found in plant based ingredients. Microbial phytases are usually classified as 3 phytases, while those from plants and fungi are known as 6-phytases. (Ravindran et al., 1995). Certain plant ingredients such as rye, wheat and barley naturally contain high levels of phytase activity (Weremko et al., 1997). Exogenous supplementation in fish feed significantly enhance phosphorus digestibility and retention across various species. However, similar positive effect is also observed in common carp, channel catfish, African catfish, striped bass, Japanese flounder and European seabass (Hua & Bureau, 2006).

Use of organic acids in improving Phosphorus utilization

Organic acids like citric acid, formic acid and EDTA help improve phophorus digestibility by dissolving bone minerals and reducing calcium-phosphorus interactions in fish intestines. Citric acid improves phosphorus utilization in rainbow trout and seabream (Sarker et al., 2005) while formic acid supplementation increases phosphorus retention in rainbow trout. Similarly, sodium citrate and EDTA enhance phosphorus digestibility from fish meal based diets.

Integrated nutritional modeling in reducing phosphorus waste

A factorial bioenergetics model called FISH-PRFEQ was developed to integrate data on phosphorus digestibility, retention and excretion in salmonid species. By using this model, aquaculture producers can estimate different forms of phosphorus waste including dissolved, solid, organic and inorganic and supports the optimization of feed formulations to reduce environmental impacts (Hua et al., 2008).

Nutritional strategies for reducing nitrogen waste output

Optimization of amino acid composition

The amino acid balance in fish diets helps minimize nitrogen waste. Excess dietary amino acids are catabolized, resulting in ammonia (NH_3) production which increases nitrogen excretion and reduces energy effeciency. Diets with an imbalanced amino acid profile reduces digestible nitrogen retention and increases losses (Cho & Woodward, 1989). Optimizing dietary amino acid composition is important though varying EAA requirement estimates and differences in evaluation methods make accurate diet formulation challanging.

Use of non protein energy sources in reducing nitrogen waste

The optimization of nitrogen excretion can be achieved by adjusting the digestible protein to digestible energy ratio (DP/DE). The supplementation of sufficient lipids reduces the use of amino acids for energy. Several species that higher lipid inclusion improves protein utilization and promotes protein sparing effect (Hua & Bureau, 2006). Azevedo et al. (2004) reported that increasing lipid levels and reducing the protein- to-lipid ratio improved nitrogen retention efficiency from 28% to 36% thus, reducing dissolved waste nitrogen.

Fish species and size specific approaches for nitrogen waste reduction

Nitrogen retention effeciency varies significantly depending on fish species, life stage and body sizes. Fish juveniles utilize feed more efficiently and retain more nitrogen than the larger fish. For example, rainbow trout above 400 g showed increased amino acid catabolism and a higher lipid-to-protein deposition ratio leading to more nitrogenous waste (Azevedo et al. 2004). Whereas, Atlantic salmon of this size did not show this pattern (Berg & Bremset, 1998). Nitrogen waste can be minimized by formulating species specific iets with optimized protein levels and balanced amino acids profiles.

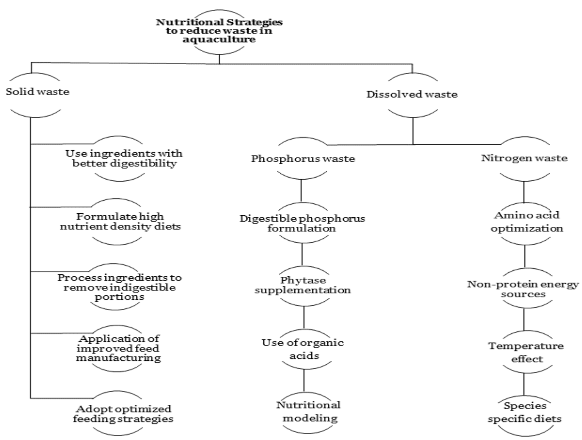

Figure 2. Nutritional strategies to reduce waste in aquaculture (Created by the authors, 2025).

Solid waste is reduced by using easily digestible ingredients, nutrient-rich diets, better feed processing and improved feeding practices. Dissolved waste is managed by controlling phosphorus through digestible formulations, phytase, organic acids and nutritional modeling while nitrogen waste can be reduced through amino acid balance, alternative energy sources, temperature control and species specific diets.

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CHAPTER V

ENVIRONMENTAL IMPACTS AND SUSTAINABLE MANAGEMENT STRATEGIES IN AQUACULTURE

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Introduction

The rapidly increasing world population and dwindling natural fish stocks have made aquaculture a key element in maintaining global food supply and nutritional security. However, the rapid growth of the sector in recent years and the intensification of production systems have also raised significant concerns regarding environmental sustainability (Jiang et al., 2022). Excessive and uncontrolled use of natural resources, particularly water, feed, energy, and land, leads to negative consequences such as deterioration of water quality, waste accumulation, habitat destruction, and loss of biodiversity This threatens both the long-term health of ecosystems and the future production potential of aquaculture. Therefore, adopting environmentally friendly production approaches, optimizing resource use, and regularly assessing environmental impacts are vital to sustainable aquaculture (Samuel-Fitwi et al., 2012).

The integration of modern technologies into aquaculture plays a critical role in achieving sustainable production goals and supports the development of environmentally, economically and socially balanced practices in the sector (Boyd et al., 2020). In this context, innovative applications such as artificial intelligence-supported monitoring systems, automatic feeding and data-driven management tools stand out as effective tools to increase production capacity while minimizing the environmental footprint of aquaculture (Mustapha et al., 2021; Huang & Khabusi, 2025). These technological advances are enabling the transition to smart aquaculture, which leverages sensors, data analytics, and artificial intelligence to optimize key elements such as fish health, feeding strategies, and water quality (Lal et al., 2024). This holistic method not only increases production volume and efficiency, but also reduces waste generation by encouraging the efficient use of resources and contributes to strengthening environmental sustainability (Rather et al., 2024). Smart aquaculture systems, which use technologies such as artificial intelligence, IoT, and big data analytics, make production processes more efficient and precise while greatly improving the sustainability of management practices (Kao & Chen, 2024). This transformation process is evolving traditional, experience-based aquaculture methods into a modern, knowledge-based industry through the application of advanced technologies (Rastegari et al., 2023).

Public acceptance is crucial for the long-term success of these technologies. Government institutions play a critical role in building trust, while certification and auditing mechanisms support market-based collaboration and sustainable practices (Pérez et al., 2025). Therefore, combining technological innovation with holistic and participatory governance that addresses environmental, economic, and social dimensions is essential for sustainable and widely accepted aquaculture practices.

2. Potential Environmental Impacts of Aquaculture

2.1. Water Pollution and Eutrophication

Eutrophication and the accumulation of micropollutants in surface waters have posed serious problems in the protection of aquatic ecosystems for many years (Kornijów, 2024). This process not only leads to an increase in algal biomass but also profoundly affects aquatic biodiversity and ecosystem functioning; the anoxic conditions that arise during the intense microbial degradation of algae cause mortality in aquatic organisms (Rabalais et al., 2010; Amorim & do Nascimento Moura, 2021). In order to control pollution and prevent ecological disasters, computer-based simulation of eutrophication transport and accumulation processes in aquatic ecosystems is used as a critical assessment and management tool and provides important information for the protection of water quality and the sustainability of ecosystem health (Anagnostou et al., 2017). The primary indicators of eutrophication in lakes are total nitrogen, dissolved oxygen, chlorophyll-a, and total phosphorus levels. In addition, some studies monitor parameters such as biochemical oxygen demand and chemical oxygen demand to more comprehensively assess water quality in lakes and aquatic systems. These parameters, by determining the organic matter content and oxygen consumption potential of water, are critical for understanding nutrient cycling in ecosystems, eutrophication levels, and impacts on fish health. Thus, water quality monitoring not only assesses environmental conditions but also contributes to the development of sustainable management strategies in aquaculture (Zhou et al., 2024; Liu et al., 2025). In addition, evaluating these parameters together provides early detection of ecological changes occurring in water bodies and contributes to the development of effective management strategies to prevent possible eutrophication risks (Akinnawo, 2023).

2.2. Sediment Accumulation and Benthic Effects

Sediment accumulation is an important process in aquatic ecosystems and has a decisive effect on the physical and biological properties of benthic environments. These sediments consist of loose particles such as sand, clay, and silt, and come from eroded soils, decomposing organic matter, and various other sources. They play an important role in the transport and dissemination of pollutants in both terrestrial and aquatic ecosystems (Bortone, 2007; Chiaia-Hernández et al., 2022). Fine sediments, in particular, play a significant role in the transport of contaminants such as pathogens, heavy metals, and nutrients. These sediments influence the distribution and accumulation of contaminants within the ecosystem, affecting benthic communities and the overall health of aquatic ecosystems (Park et al., 2019). This transport process means that nutrient-rich sediments can promote eutrophic conditions, triggering algal blooms, significantly reducing species diversity and negatively impacting aquatic ecosystem functioning (Cooper et al., 2019). Furthermore, the persistent accumulation of heavy metals in bottom sediments, especially in deeper regions where pressure and temperature favor the formation of inorganic compounds, not only threatens ecosystem health but also poses significant risks to energy infrastructure and the sustainable management of water resources (Przysucha et al., 2025). Therefore, regular monitoring of heavy metal accumulation in bottom sediments and implementation of appropriate environmental management strategies are vital for both protecting ecosystem health and ensuring the safety of water resources open to human use (El-Sharkawy et al., 2025).

2.3. Chemical and Antibiotic Use

The use of chemicals and antibiotics in aquaculture is widely used for disease control, growth promotion and water quality protection (Subasinghe et al., 1996; Bondad-Reantaso et al., 2005; Rico et al., 2013; Hasan et al., 2017). However, excessive or unconscious use of these substances can cause serious environmental and health problems such as the development of antimicrobial resistance, accumulation of chemical residues in aquatic ecosystems and adverse effects on non-target organisms (Okocha et al., 2018; Felis et al., 2020). Particularly in intensive fish farms, the aquatic environment serves as an important reservoir for these resistant bacteria, facilitating their spread to terrestrial ecosystems, food processing facilities and human communities (Milijasevic et al., 2024). The widespread use of antimicrobials in aquaculture leads to the dissemination of approximately 80% of these compounds into the environment without losing their biological activity, thus selecting for resistant bacteria (Cabello et al., 2013). This persistent presence of antimicrobials in aquatic environments significantly alters the biodiversity of microbial communities, replacing susceptible strains with resistant ones (Guardone et al., 2021). These residues are taken up by aquatic organisms such as plankton, benthic organisms and fish, accumulate along the food chain and ultimately cause indirect effects on human health (Rose et al., 2023). This bioaccumulation can compromise immunity, leading to chronic organ failure, hypersensitivity reactions, and alterations in the human gut microbiota (Ende et al., 2024). Antimicrobial stewardship does not solely focus on reducing antibiotic use; it also requires a holistic and coordinated strategy encompassing elements such as infection control, clinical microbiology, antimicrobial monitoring, medication safety surveillance, education, protocols, and legislation. While many veterinarians are aware of the importance of antimicrobial resistance, antimicrobial stewardship practices in veterinary medicine are not yet fully mature. Strong collaboration between human and animal health can significantly contribute to implementing a holistic and sustainable approach to combating antimicrobial resistance (Caneschi et al., 2023).

2.4. Habitat Degradation

The widespread development of aquaculture in recent decades, particularly the conversion of mangrove forests and other coastal habitats into aquaculture ponds, has led to significant ecological degradation through altered hydrological regimes and the decline of vital ecosystem services (Tahiluddin et al., 2025). Coastal wetlands (salt marshes, mangroves, etc.) are of great ecological and economic importance to aquaculture production by providing natural breeding, feeding, and sheltering grounds for fish, crustaceans, and other aquatic organisms. However, uncontrolled aquaculture activities in these areas, particularly with intensive feeding and the use of antibiotics and chemicals, increase environmental pressures. Overproduction practices result in organic matter accumulation, oxygen depletion, eutrophication, and water pollution. Furthermore, mangrove clearing and shoreline filling for new facilities lead to habitat loss and biodiversity decline. This not only jeopardizes the health of ecosystems but also jeopardizes the sustainability of fisheries. Adopting environmentally sound and ecosystem-focused aquaculture management strategies is critical to protecting coastal wetlands (Newton et al., 2020). Such management strategies are crucial to reduce the negative environmental impacts that aquaculture can cause, such as degradation of freshwater and coastal ecosystems, pollution, eutrophication and increased pathogen spread (Nie & Hallerman, 2021).

2.5. Fish Health and Disease Risks

Aquaculture is an important production method for meeting the growing global demand for seafood. However, the environmental impacts of this industry raise significant concerns, particularly regarding fish health and disease management. Factors such as high stocking densities, water quality degradation, and biodiversity loss can contribute to the spread of diseases and fish health problems (Garlock et al., 2024). Diseases spread rapidly in aquaculture, leading to production losses. Piscirickettsia salmonis particularly affects salmon production in Chile, causing high mortality and economic losses. The bacteria is transmitted through the intestines, gills, and skin, and infects various salmon species. Stress, high fish densities, and the intensive use of antimicrobials in salmon farming can trigger disease. Many of the antimicrobials used leach into the water, contributing to the spread of resistant bacteria (Cabello et al., 2025). Climate change accelerates the proliferation of pathogens and the spread of diseases by increasing water temperatures. Research by Okon (2024) indicates that rising water temperatures pose a serious threat to aquaculture and fisheries and impact the course of fish diseases. These effects, combined with environmental factors such as pH, salinity, and ocean acidification, present additional challenges to fish health. Therefore, comprehensive strategies and advanced research are needed to effectively manage these issues in the future. Vervelacis (2025) examined the economic costs of mortality in RAS and sea cage systems in rainbow trout aquaculture, showing that most of the costs are due to feed and biomass loss, while medication costs have a significant impact. While disease management was relatively successful in the freshwater system, profits remained positive up to 57% mortality in the saltwater system. The study highlights the importance of effective disease control and preventing disease introduction into RAS systems. Machine learning-based systems are an effective tool for predicting fish disease risks by analyzing water quality data (Nayan et al., 2021; Kumar et al., 2023). Biosecurity measures are critical to preventing the emergence of diseases in aquaculture and controlling the spread of existing ones. These measures include regular disinfection of facilities and equipment, training of personnel on diseases and hygiene, quarantining new stock, and preventing the introduction of potential pathogens. Furthermore, good practices such as feed management, appropriate water quality control, and continuous monitoring of environmental parameters play a significant role in maintaining fish health and minimizing stress levels. These comprehensive biosecurity practices increase production efficiency through early detection and prevention of disease spread, while also contributing to the creation of a sustainable and safe aquaculture environment (Mazzucato et al., 2023). To meet the growing demand for aquaculture, Internet of Things (IoT)-based environmental control systems have been developed. These systems optimize production processes by collecting and analyzing data such as water temperature, pH, humidity, and fish behavior in real time using wireless sensors. As a result, fish health and productivity are improved, resource use and waste are reduced, and a more sustainable and profitable aquaculture environment is achieved (Dhinakaran et al., 2023).

3. Environmental Impacts of Fish Farming Systems

Various techniques are used in fish farming, and the preferred methods vary depending on the characteristics of the facility, the water exchange rate, and the density of the growing area. Regional conditions, climate characteristics, and the type of fish to be raised are also taken into account when choosing a method (Ahmad et al., 2021). Different aquaculture systems are used to provide optimal living conditions for fish and increase production efficiency. The most commonly used fish farming methods include closed water systems, pond farming, aquaponics systems, and marine farms (Turlybek et al., 2025).

3.1. Recirculating Aquaculture Systems (RAS)

RAS systems are systems established on land where fish are reared in tanks in closed, controlled environments. In these systems, water is reused through mechanical/biological filtration, sterilization, and oxygenation processes (Badiola et al., 2012; Dalsgaard et al., 2013; Ahmed & Turchini, 2021). RAS is considered an environmentally sustainable aquaculture method because it reduces water usage, improves waste management, and enables nutrient recycling (Martins et al., 2010; Murray et al., 2014; van Rijn, 2013). This innovative approach optimizes resource use in line with the principles of the water-energy-food relationship, while providing significant advantages, especially in regions experiencing water scarcity, thanks to its capacity to recycle and reuse 90-99% of water (Zhang et al., 2023). This high water savings allows for a significant reduction in the ecological impact caused by the continuous discharge of large quantities of fresh or brackish water in conventional aquaculture (Moore et al., 2020).

3.2. Pond Farming

Pond farming, also known as "organic aquaculture," refers to the production of fish in open systems. This ancient method is still effective and is preferred by agriculturalists. A pond both enhances the landscape and offers the opportunity for fish production (Chakroff, 1984; François et al., 2010). In many countries around the world, fish farming is generally carried out in ponds. However, the majority of pond producers lack sufficient knowledge about water quality management. With proper management and the adoption of water quality management practices, high fish production can be achieved at low cost. Parameters such as temperature, pH, ammonia, nitrite, nitrate, oxygen, transparency, and plankton density are critical for maintaining healthy water quality and natural nutrient resources in ponds (Bhatnagar & Devi, 2019). In pond farming, soil structure affects the fish indirectly by affecting the water parameters (Shafi et al., 2021). The soil structure at the pond bottom plays an important role in the nitrogen concentration, carbon/nitrogen (C/N) ratio and distribution of other organic matter (Hasibuan et al., 2023). The microbiota also plays an important role in pond fishing systems. Plankton, zooplankton, and various bacterial species break down and consume dead organic matter in the water. When nutrients are limited, fish feed on plankton, thus forming the beginning of the food chain. However, this microbial community can occasionally have negative effects on fish. They proliferate rapidly at night and can consume dissolved oxygen, causing oxygen depletion in the water (Boyd, 1982). Decreasing DO levels causes increased stress in fish, increasing their risk of mortality. Depending on their environment, fish can experience fluctuations in oxygen levels, ranging from hypoxia (low oxygen availability) to hyperoxia (oversaturation of oxygen) (Diaz & Breitburg, 2009). Pond farming interacts more directly with the environment than other farming systems and can lead to waste accumulation in the water. Eutrophication can negatively impact fish health, so ecological engineering practices are critical (Muendo et al., 2006). On the other hand, the sediments accumulated in fish farming ponds may offer some environmental advantages. These sediments contain high levels of nutrients such as sodium, potassium, and phosphorus. Furthermore, fish waste can be recycled through various processes and converted into organic fertilizers that can be used as plant nutrients (Muendo et al., 2006; Adedeji et al., 2021).

3.3. Aquaponic Ecosystem Farming

Aquaponic systems combine aquaculture, hydroponic methods, and beneficial microorganisms to create a sustainable and integrated production model. In this system, fish waste is used as a rich nutrient source for plants, while plants naturally purify the water and recycle it back into the production cycle. This facilitates waste management and water reuse. The aquaponic approach not only ensures environmentally friendly production but also supports sustainability in organic food production, optimizes resource use, and increases economic efficiency. This method offers long-term advantages in terms of both production and ecological balance through the effective management of water, nutrients, and energy resources (Krastanova et al., 2022). Bacteria play an extremely important role for optimal growth of species in aquaponic systems (Rudoy et al., 2025). These microbial communities facilitate the conversion of aquaculture waste products into bioavailable nutrients for plant uptake, thereby supporting the dual production of aquatic organisms and crops (Emerenciano et al., 2025). This integrated approach leverages ecological principles, such as the utilization of waste from one biological system as a nutrient source for another, to enhance overall system efficiency and sustainability (Bhattacharjee, 2025). This symbiotic relationship not only mitigates the environmental impact associated with traditional aquaculture and agriculture but also minimizes water consumption through continuous recirculation and nutrient cycling (Calone et al., 2019; Gayam et al., 2022). This dual functionality allows aquaponics to address challenges in food security by producing two marketable products-aquatic animals and plants-while significantly reducing the water footprint compared to conventional agricultural practices (Romano & Islam, 2023; Goda et al., 2024). In aquaponics, the recirculation of water creates a closed-loop system that efficiently removes fish waste and decomposed food particles, returning clean water back to the fish tanks (Hutagalung et al., 2023). This innovative integration reduces water consumption and the reliance on external fertilizers, offering a highly resource-efficient approach to food production (Chandramenon et al., 2024). Aquaponically raised fish have a more balanced and healthy profile of omega-6 and omega-3 fatty acids thanks to controlled growing conditions and natural nutrient cycling. This balanced fatty acid profile supports consumers' cardiovascular health by helping reduce inflammation, improve blood lipid levels, and lower the risk of cardiovascular disease. Therefore, aquaponic fish not only provide high-quality protein and essential amino acids, but also gain value as a functional food thanks to their omega-3-rich fatty acids. With these characteristics, aquaponic systems enhance the nutritional value of fish products, offering significant health and economic benefits for both consumers and producers (Hough et al., 2016). Location selection for commercial aquaponics businesses is shaped by factors such as proximity to local markets, restaurants that prioritize sustainable ingredients, and direct-to-consumer sales opportunities. Economic viability is directly related to access to these markets. While the first European aquaponics initiatives focused on production and technology, certification, regulations, and marketing are increasingly important today (Miličić et al., 2017).

3.4. Marine Farming

Marine farms and pond systems are considered important examples of organic aquaculture. Also known as mariculture, marine farming involves the cultivation of aquatic organisms directly in the marine environment, either throughout the production process or at specific growth stages (Braña et al., 2021). Most marine fish farms are located in shallow, sheltered, near-shore waters to ensure safe facility operation and easy access to services required for feeding, hatchery, storage, maintenance, and post-harvest operations (Chu et al., 2020). Mariculture farms, like pond farming, produce wastewater containing fish waste and chemicals. Discharge of these wastes into the sea can cause environmental problems such as oxygen depletion, eutrophication, heavy metal pollution, and habitat degradation. Excess organic matter and nutrients, primarily nitrogen and phosphorus, stimulate algal blooms, which deplete dissolved oxygen levels and alter marine biodiversity (Holmer et al., 2008; Carballeira et al., 2018).

Moreover, uneaten feed and fecal waste accumulate in sediments beneath cages, leading to changes in benthic community structures and reduced sediment quality (Kutti et al., 2007; Price et al., 2015). Antifouling paints and feed additives, in particular, play a significant role in increasing marine pollution. These products cause heavy metals such as copper and zinc to accumulate in water and sediments, negatively impacting the ecosystem. These heavy metals can be toxic to marine organisms and, by entering the food chain, threaten biodiversity and ecosystem health. Furthermore, metal accumulation reduces water quality, negatively impacting fish and other aquaculture production, and further exacerbates marine pollution (Dean et al., 2007; Brooks & Mahnken, 2003). To mitigate these negative impacts, integrated multi-trophic aquaculture (IMTA) and improved waste management practices are recommended as environmentally sustainable alternatives (Troell et al., 2009; Chopin et al., 2012).

7. Conclusion

Aquaculture has gained importance as one of the most efficient and sustainable production methods to meet the increasing global demand for aquaculture products. However, the rapid development of the sector has made it necessary to carefully evaluate the environmental impacts of different aquaculture systems. This study demonstrates that while aquaculture is strategically important for food security, it also places significant pressures on aquatic ecosystems through nutrient discharge, sediment accumulation, habitat alteration, and disease risks. Water pollution and eutrophication from aquaculture activities are often linked to overfeeding and accumulation of organic matter. Similarly, sediment accumulation and the resulting changes in benthic structure lead to oxygen depletion and reduced biodiversity. While the use of antibiotics and chemicals may provide short-term benefits in disease control, they increase the long-term risks of antimicrobial resistance development and biocumulative contamination. Furthermore, the conversion of wetlands, mangroves, and coastal ecosystems to aquaculture areas causes significant environmental problems, such as habitat loss and the disruption of ecosystem integrity. Increasing aquaculture density also increases the risk of disease transmission, highlighting the need for effective biosecurity measures. When evaluated on a system-by-system basis, recirculating aquaculture systems (RAS) stand out as the most environmentally friendly and controlled method thanks to advanced filtration and water recycling technologies. While pond farming is a low-cost and traditional method, it can lead to nutrient overload and sedimentation problems if appropriate management strategies are not implemented. Aquaponic systems stand out as an innovative model that integrates fish and plant production, enabling nutrient recycling and reducing waste generation. Mariculture, on the other hand, while enabling the production of high-nutrient fish, presents environmental challenges specific to coastal and offshore ecosystems, such as wastewater discharge, biofouling, and habitat degradation. Looking forward, the primary goal of sustainable aquaculture should be environmental responsibility and ecosystem-based management. Circular resource use, eco-engineering-based system designs, microbial biofilters, and precision feeding strategies are important tools for reducing the environmental footprint. Furthermore, policy regulations should be developed to support multi-trophic aquaculture practices, spatial planning, and continuous environmental monitoring mechanisms. The long-term sustainability of aquaculture depends on maintaining production efficiency in a balanced manner while preserving ecological integrity.

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CHAPTER VI

INNOVATIONS IN AQUACULTURE TECHNOLOGY AND AUTOMATION

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Introduction

Aquaculture is one of the fastest-growing food sectors globally and now provides nearly half of the world's fish for human consumption (Anderson et al., 2017). It is regarded as a highly profitable industry due to the wide variety of fish species available that are both palatable and nutritious (Prabu et al., 2017). According to global aquaculture production data, the sector contributed approximately 171 million tonnes to total fish production in 2016, with about 88% (over 151 million tonnes) of this output utilized directly for human consumption (FAO, 2018). This reflects aquaculture's increasing importance in meeting global seafood demand and supporting food security. Production growth in aquaculture during recent decades has been remarkable, with global production increasing from 2.6 million metric tons (mt) in 1970 to 87.5 million tonn in 2020 (FAO, 2022).

Rising population and growing health awareness are driving increased demand for aquatic products, which has led to the expansion and intensification of aquaculture practices (Campanati et al., 2022; Rosa et al., 2020). Nevertheless, this intensification brings forth several critical challenges, including ensuring the sustainable use of natural resources, maintaining optimal water quality, preventing disease outbreaks, and managing production efficiently. Addressing these challenges is essential for the continued growth and sustainability of the aquaculture sector. Innovations in aquaculture technology and automation are transforming fish farming by improving efficiency, sustainability, and productivity to meet the growing global demand for seafood (Mustafa et al., 2021). Traditional aquaculture methods face challenges such as inefficient resource use, disease outbreaks, environmental impact, and high labor costs. Automation addresses these issues by streamlining operations, enhancing data collection, and enabling precise control over environmental conditions. Technologies like Recirculating Aquaculture Systems (RAS), automated feeding systems, water quality sensors, and underwater robotics facilitate continuous monitoring and optimal management of fish farms, resulting in improved growth rates, reduced feed waste, and healthier stock (Armaah, 2024; Rabia et al., 2023).

Artificial intelligence (AI) and the Internet of Things (IoT) have emerged as core components of modern aquaculture, enabling real-time data-driven decision-making through smart sensors and cloud computing. AI algorithms optimize feeding strategies, predict growth patterns, and detect disease early, enhancing productivity and minimizing losses. IoT devices facilitate remote and automated monitoring of parameters such as temperature, pH, dissolved oxygen, and fish behavior, reducing manual labor and increasing farm safety. In aquaculture, AI is uniquely applied to tackle dynamic and heterogeneous environments involving biological systems, fluctuating water quality, and species-specific behaviors. The integration of artificial intelligence (AI) into aquaculture offers the potential to significantly enhance the precision and effectiveness of various operational processes. AI enables real-time monitoring of critical parameters such as water quality, fish behavior, and feeding activity, allowing for timely and proactive interventions that are essential for maximizing productivity. This technology supports more accurate decision-making, resulting in improved health and welfare of cultured species, optimized resource use, and minimized environmental impacts. By automating routine tasks and providing predictive analytics, AI not only boosts efficiency but also helps prevent diseases and reduces operational costs, thus fostering sustainable aquaculture development. Figure. 1 presents a holistic overview of AI-driven applications and emerging trends in aquaculture, highlighting their role in advancing the field.

While extensive research has reviewed AI technologies in fields like manufacturing and precision agriculture, there remains a lack of comprehensive studies addressing AI's role within aquaculture as a whole. Much of the existing literature has focused on isolated aspects such as feeding optimization, dissolved oxygen management, or disease detection, without providing an integrated view of the sector's technological progress. This book chapter aims to address this gap by delivering a holistic detail of Innovations in aquaculture, AI applications across key areas including water quality management, disease prevention, feeding automation, breeding strategies, and product traceability, offering a united perspective on how AI is advancing aquaculture as a whole.

Fig.1

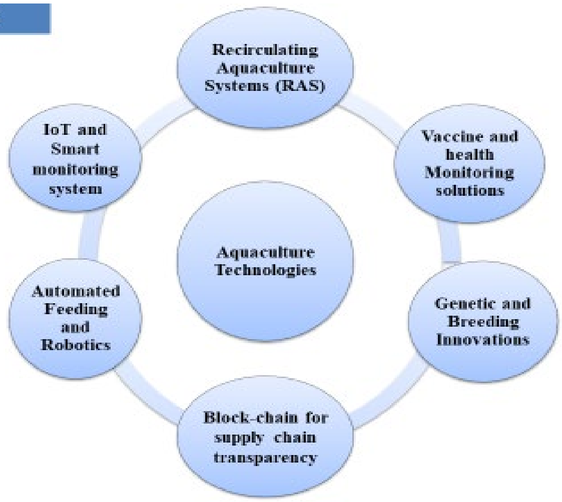

Figure 1. Holistic overview of AI-driven applications and emerging trends in aquaculture (Yang et al., 2025).

2. Emerging Technologies in Aquaculture

Aquaculture has emerged as a critical sector for global food security, surpassing wild fish captures in production. To meet the rising demand for seafood sustainably, the industry is adopting advanced technologies that improve efficiency, environmental sustainability, and product quality.

2.1 Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are a transformative technology in modern aquaculture that allow for highly efficient and sustainable land-based fish farming through closed-loop water reuse (Lal et al., 2024). Recirculating Aquaculture Systems (RAS) represent a key innovation in aquaculture technology by enabling controlled environment farming with minimal water usage. These systems are designed as closed-loop or semi-closed water systems that reuse and continuously treat water through mechanical and biological filtration, disinfection, and oxygenation (Kamali et al., 2022; Turlybek et al., 2025). It is a closed system that involves housed fish in tanks where water is continuously recirculated and treated by a filtration system to guarantee optimum growing conditions is (Meisch & Stark, 2019). In a typical Recirculating Aquaculture System (RAS), water continuously flows from the fish tanks through a multi-stage filtration system before returning to the tanks (Luo, 2023) (Figure 2). Fish metabolism results in water leaving the tanks laden with solids, nutrients, and carbon dioxide while being low in oxygen compared to the inflow water. The filtration system aims to remove these solids, reduce nutrients and toxins, decrease carbon dioxide levels, and increase dissolved oxygen before water re-enters the fish tanks (Mishra, 2023).

The first stage involves solids separation, where feed residues, feces, and bacterial aggregations are removed from the water. Next, the water is disinfected using ultraviolet (UV) light, though this step may be placed differently depending on the farm setup or omitted entirely (Schumann, 2021). The water then passes through the biofilter, where bacteria metabolize organic matter and convert harmful ammonia into nitrite and then nitrate, consuming dissolved oxygen and producing carbon dioxide. Therefore, after bio filtration, the water undergoes degassing to increase the water-to-air surface area, allowing carbon dioxide to escape into the air (Suriasni et al., 2023). Finally, oxygenation units raise the dissolved oxygen concentration to levels suitable for fish health before the water is returned to the tanks. These components work together to maintain water quality essential for fish growth and system sustainability (Lindholm-Lehto, 2023). There is considerable scope to increase freshwater (and seawater) aquaculture production via recirculating aquaculture systems (RAS). These systems enable recycling of water and regulation of temperature, water quality and improved biosecurity, while minimizing environmental impacts and allowing aquaculture production to be located near markets across a wide geographical range including coastal and inland areas, thus reducing transport and carbon costs and enabling fresher products to reach consumers (Crouse et al. 2021; Davidson 2020; Lazado and Good 2021).

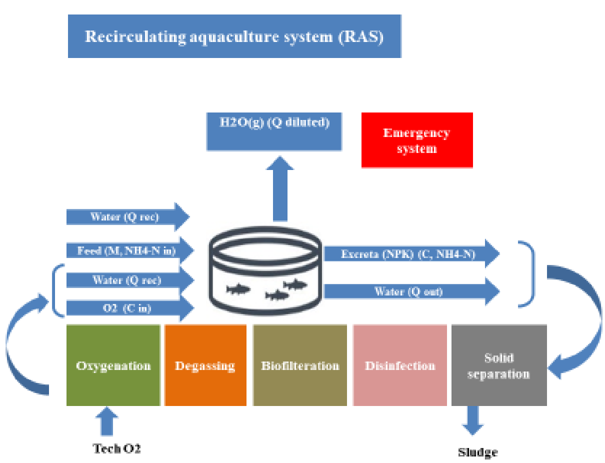

Figure 2. Recirculating aquaculture syystems (Farghally et al., 2014).

2.2 Biofloc Technology

Biofloc technology (BFT) is an innovative and eco-friendly approach in aquaculture that involves the use of microbial aggregates, known as bioflocs, to recycle nutrients and improve water quality while simultaneously providing a supplemental protein-rich feed source for aquatic organisms (Kumar et al., 2024). Biofloc technology (BFT) is rapidly gaining recognition as a forward-thinking and sustainable approach in aquaculture. It offers a dual advantage by addressing environmental concerns and economic needs. This innovative method significantly cuts down water consumption and reduces the discharge of waste effluents, making aquaculture more eco-friendly. Additionally, it lessens the reliance on artificial feeds by transforming waste into valuable feed resources, thereby decreasing the cost of production. Also, BFT enhances biosecurity by minimizing water exchange, which reduces the chances of disease introduction from external sources (Khanjani et al., 2020). This system relies on the cultivation of heterotrophic bacteria that convert nitrogenous waste, such as ammonia from fish excreta and uneaten feed, into microbial biomass through a controlled carbon-to-nitrogen ratio, often aided by carbon sources like molasses. Continuous aeration maintains oxygen levels and distributes the bioflocs evenly in the rearing water (Ogello et al., 2024). Biofloc represents a symbiotic phenomenon characterized by the coexistence of various aquatic organisms, heterotrophic bacteria, and numerous other species of microbes within the aquatic environment (El-Sayed, 2021). According to Browdy et al. (2012), the elimination of ammonia from the culture system facilitates the recycling of waste materials into supplementary food sources for farmed aquatic animals. The microbial communities in bioflocs not only help in bioremediation by assimilating waste nutrients but also enhance the growth performance, immune response, and disease resistance of cultured species such as shrimp (Litopenaeus vannamei), tilapia, catfish, and pangasius. A major advantage of BFT is its minimal water exchange requirement, leading to significant conservation of water resources and reduction of environmental pollution from aquaculture effluents (Khanjani et al., 2024). This technology is recognized for its sustainability, cost-effectiveness, and ability to increase production efficiency by reducing feed costs and improving biosecurity. Overall, biofloc technology represents a promising future for sustainable aquaculture by balancing environmental concerns with economic benefits, supporting food security with a reduced ecological footprint (Ogello et al., 2021).

The key benefits of Biofloc Technology (BFT) in aquaculture include several significant aspects that contribute to sustainability, cost-effectiveness, and productivity. Firstly, BFT enhances resource efficiency by requiring less water and space than traditional aquaculture systems, enabling intensive farming in smaller ponds without compromising production (Ogello et al., 2021). It also effectively recycles nitrogenous waste such as ammonia, converting it into microbial biomass that serves as a natural, protein-rich supplementary feed, thereby reducing reliance on costly artificial feeds and lowering feed costs by 30–40% (Khanjani et al., 2025). Another key benefit is the promotion of faster growth rates and better health of cultured species, supported by improved immune responses and disease resistance due to the beneficial microorganisms present in the biofloc. The consumption of biofloc by fish or shrimp has been demonstrated to offer numerous benefits, including an enhanced growth rate, reduced feed conversion ratio (FCR), and lower related expenses (Becerril-Cortés et al., 2018). BFT also contributes to environmental sustainability by drastically reducing water exchange needs, conserving scarce water resources, and minimizing the ecological footprint of aquaculture operations. Commercially, the system has demonstrated success with high production yields and has become a viable alternative for sustainable aquaculture practices worldwide. However, it requires technical expertise and continuous aeration for optimal functioning (Braga et al., 2023).

2.3 Genetic and Breeding Technologies

Genetic and breeding technologies play a transformative role in modern aquaculture, offering cutting-edge tools to enhance the productivity, sustainability, and resilience of cultured aquatic species. These technologies focus on selecting and improving desirable traits in fish and shellfish, such as faster growth, disease resistance, and environmental adaptability, by harnessing advanced genetic knowledge and breeding practices (Behera, 2024). Fundamental approaches include traditional selective breeding, where individuals with superior characteristics are chosen as breeders, as well as sophisticated methods like marker-assisted selection and genomic selection, which use genetic markers to identify and select the best candidates more precisely. Techniques such as hybridization, sex reversal, and chromosome manipulation further expand the possibilities for producing improved strains tailored for specific aquaculture conditions (Ganesan & Moulali, 2025).

Artificial breeding, often involving hormone-induced maturation, enables controlled reproduction of species, accelerating seed production and reducing generation times. This advancement is crucial for meeting rising global seafood demands by increasing supply without overexploiting wild populations (Weber et al., 2013; Behera, 2024). Additionally, innovations like sperm cryopreservation and stem cell technologies enhance genetic resource management and long-term breeding programs' sustainability. Genetic modification and transgenesis techniques also hold promise for introducing beneficial traits, though they require careful regulatory and ethical considerations (Engdawork et al., 2024).

2.3.1 Advances in selective breeding and genome editing (CRISPR, SNPs)

More recently, genome editing technologies, especially CRISPR/Cas9, have started to reshape aquaculture breeding. CRISPR allows scientists to precisely modify specific genes responsible for beneficial traits without introducing foreign DNA, thus addressing some regulatory and public concerns associated with genetically modified organisms (GMOs) (Gupta et al., 2021). This technique has been applied to improve traits including enhanced growth rates, disease resistance, reproduction control, and environmental adaptability across various aquaculture species such as salmon, tilapia, and shrimp (Zhu et al., 20240. The technology not only speeds up the breeding cycle sometimes reducing the time to establish new breeds to 1–3 generations but also increases the accuracy and efficiency of trait modification (Begna, 2022).

The potential of CRISPR also extends to generating pathogen-resistant strains and reducing environmental impact by improving feed conversion efficiency and lowering nitrogen waste production. Despite its promise, challenges remain, including technical hurdles, ethical considerations, regulatory frameworks, and the need for public acceptance (Verdegem et al., 2023). These technologies have already made significant impacts in aquaculture sectors globally, improving species such as salmon, shrimp, oysters, and tilapia. Beyond productivity gains, breeding technologies contribute to ecosystem stability by fostering disease-resistant and faster-growing populations, reducing environmental impacts. As global seafood demand grows, the integration of genetic and breeding technologies is vital to advancing sustainable aquaculture production that can support food security and economic development while preserving biodiversity and aquatic ecosystems (Mohd & Mushtaq, 2025).

2.3.2 Development of disease-resistant and climate-resilient species

The development of disease-resistant and climate-resilient aquaculture species is a critical focus for ensuring sustainable seafood production in the face of growing environmental and biological challenges. Disease outbreaks pose a significant challenge to the growth and sustainability of aquaculture (Abisha et al., 2022; Saini et al., 2024). To combat these issues, biotechnological advances have become increasingly important, particularly molecular diagnostic tools, vaccines, and immune stimulants, which enhance disease resistance in fish and shellfish worldwide. Rapid and accurate detection of pathogens is critical, especially for viral infections where prevention is key (Mishra et al., 2023). Molecular techniques such as polymerase chain reaction (PCR) and the use of gene probes have emerged as powerful tools for early and precise identification of various pathogens affecting aquaculture species (Abdelsalam et al., 2023). These methods enable timely intervention, reducing the spread and impact of diseases. Over the years, PCR-based diagnostics and gene probes have been developed for numerous aquatic pathogens, aiding fish and shrimp health management and improving the overall effectiveness of disease control in aquaculture systems (Dong et al., 2023). Selective breeding programs have made significant progress by identifying and enhancing genetic traits that confer resistance to prevalent diseases such as White Spot Syndrome Virus in shrimp and bacterial infections in fish like catfish and kingfish (Nguyen, 2024). These programs utilize genetic diversity within populations to achieve notable improvements in survival and overall health, often achieving genetic gains of around 12-13% per generation. In addition to disease resistance, breeding efforts increasingly target traits that improve species' ability to withstand climate-related stresses such as temperature fluctuations and water quality changes, making them more resilient to shifting environmental conditions (Paniza, 2024).

Advancements in genomic technologies and precision farming tools, including AI, omics approaches and computer-assisted selection models (ML), are accelerating the identification of superior breeding candidates, enabling more effective and sustainable selection strategies (Visakh et al., 2024). AI has enabled significant advances in precision breeding by integrating genetic and environmental data to optimize breeding strategies (Wang et al., 2024). Machine learning models analyze the complex interactions between genetics and environmental conditions, helping to identify the most effective breeding approaches tailored to specific aquaculture settings. These results in improved survival rates, accelerated growth, and enhanced resilience of cultured species (Bargelloni et al., 2021; Palaiokostas, 2021). This integration of genetics and environmental adaptability leads to robust aquaculture stocks that maintain productivity under disease pressure and adverse climatic conditions. Such resilient strains not only enhance farm profitability and reduce reliance on chemical treatments but also contribute to environmental sustainability by lowering disease outbreaks and mortality rates.

2.3.2 Probiotics, prebiotics, and microbial management for sustainable aquaculture

Probiotics, prebiotics, and microbial management have emerged as vital strategies for promoting sustainable aquaculture by enhancing the health, growth, and disease resistance of aquatic species. Probiotics are beneficial live microorganisms, such as Bacillus, Lactobacillus, and Arthrobacter, that when added to aquaculture systems or feed, help establish and maintain a healthy gut microbiota in fish and shellfish (Fachri et al., 2024). This improved gut environment boosts nutrient absorption, stimulates the immune system, and inhibits harmful pathogens, leading to healthier and more resilient aquaculture species. Probiotics can be used to enhance growth, improve feed utilization, strengthen immune function, and improve water quality in aquaculture. In aquaculture, probiotics must possess antimicrobial properties while ensuring safety for the host species, the aquatic environment, and human consumers (Tabassum et al., 2021). To qualify as effective probiotics, microorganisms must fulfill specific criteria. Key factors in selecting probiotics include originating from the host species to ensure compatibility, demonstrating strain safety with no harmful effects, and the ability to produce substances that inhibit harmful bacteria (Nur, 2020).

Additionally, a successful probiotic should be capable of modulating the host's immune system positively and effectively competing with pathogens for adhesion sites in the intestinal mucosa, thereby preventing pathogenic colonization. These characteristics collectively ensure that probiotics contribute to enhancing the health and disease resistance of aquatic animals while maintaining ecological balance and consumer safety (Madhulika et al., 2025).

Prebiotics, often non-digestible food ingredients, support the growth and activity of these beneficial microbes, further enhancing their positive effects on host health. Prebiotics are indigestible fibres fermented by gut enzymes and commensal bacteria, whose beneficial effects are due to the by-products generated from fermentation (Lordan et al., 2020). The influence of pre-biotics on the immune system of fish is called immuno-saccharides. In mammals, prebiotics exert their effects primarily through interactions with the intestinal mucosa, influencing the relationship between gut morphology and the resident microbiota. Similarly, studies in fish and shellfish have demonstrated that dietary prebiotics positively impact various parameters, including growth rates, modulation of gut microbiota, and enhanced resistance to pathogenic bacteria. They also improve innate immune responses, such as alternative complement activity (ACH50), lysozyme activity, natural hemagglutination, respiratory burst, superoxide dismutase activity, and phagocytic activity. These findings indicate that incorporating prebiotics into aquaculture diets functions as an effective immuno-stimulant, offering a valuable alternative strategy for the prevention and control of diseases in aquaculture species, reducing dependency on antibiotics and chemicals (Akhter et al., 2015; Carbone & Faggio, 2016).

3. Automation in Aquaculture Operations

Aquaculture is one of the fastest-growing sectors in the global food industry and now supplies nearly half of the fish consumed by people worldwide. This sector is highly profitable due to the wide variety of fish species cultured, which are not only flavorful but also provide nutritious, healthy food options.

3.1. Automated Feeding Systems

Over the past decade, aquaculture has emerged as the fastest-growing sector in the global food industry (Aanesen et al., 2023). A key factor driving this expansion is the remarkable efficiency of fish farming, particularly in terms of feed conversion rate (FCR) and carbon footprint. Compared to other protein production industries, aquaculture exhibits a low FCR, meaning it can produce a higher yield of animal protein using less feed (Cantillo et al., 2023). This efficiency not only supports sustainable production but also contributes to meeting increasing global seafood demand while minimizing environmental impacts (Yi and Kim, 2020a). Another related factor is the increasing demand for seafood products due to population growth (Luna et al., 2023), which has pushed the salmon industry to rapid growth and significant economic success. The continued expansion and diversification of aquaculture contribute significantly to meeting the increasing demand for sustainable protein sources globally (Boyd et al., 2022). In any aquaculture operation, key factors such as fish growth, health, and reproductive capability heavily rely on providing an adequate amount of high-quality feed. It is crucial to optimize feeding times and quantities to match the nutritional needs of the fish (Bhat et al., 2025). Proper adjustment of feeding ensures maximized income and benefits by improving growth performance and feed efficiency (Henriksson et al., 2021). Feeding frequency plays a significant role in influencing these outcomes, impacting not only the growth rates and feed utilization but also the overall economic viability of the operation (Liang et al., 2025). Overfeeding can lead to wasted feed, increasing production costs and causing pollution in the aquatic environment. Conversely, underfeeding can negatively affect fish health and stunt growth (Duan et al., 2025). Since feed expenses typically constitute the largest operational cost in aquaculture, effective feed management remains a challenging yet essential aspect for successful and sustainable aquaculture production (Munguti et al., 2021).

To reduce competition for space in coastal zones and expand salmon production, offshore aquaculture has increasingly attracted attention in recent years. This innovative approach involves relocating salmon farms further from the shoreline into more exposed, less protected ocean environments (Carroza-Meza et al., 2024). Moving farms offshore offers several benefits, such as better water exchange, which improves oxygen levels and disperses waste and potential pathogens more effectively than in sheltered coastal areas. Offshore locations can also help alleviate issues like sea lice infestations and harmful algal blooms that are common in nearshore fjord or loch farming (Morro et al., 2022). By positioning farms in open waters with stronger currents and waves, producers can increase production capacity while potentially reducing environmental and disease-related challenges. This transition to offshore farming, however, requires robust infrastructure and technology to withstand harsh marine conditions, and careful site selection is essential to balance productivity, environmental sustainability, and fish welfare (Watson et al., 2022). One crucial support system for offshore aquaculture is fish feeding management, which includes both the feeding equipment and the coordination of feeding activities (Long et al., 2024). Given that offshore aquaculture units are located far from the coast, automated fish feeding equipment is an ideal choice. An automatic fish feeder is a device designed to supply food to fish at scheduled intervals without human intervention (Thornburg, 2025). It operates by integrating mechanical and electrical components, enabling precise and consistent feeding that replaces the need for manual feeding by personnel. This automation enhances feeding efficiency, reduces labor costs, and ensures optimal nutrition delivery in remote offshore environments (Ahmad et al., 2025).

3.2. Water Quality Monitoring and Control

Water Quality Monitoring and Control systems employ sensors to continuously measure critical parameters such as dissolved oxygen, pH, ammonia, nitrates, and temperature (Zainurin et al 2022). Automated controls adjust filtration, aeration, and water flow in real time to maintain optimal conditions, preventing stress and disease in aquatic livestock. This real-time monitoring ensures stable environments, improving overall fish health and productivity (Nayoun et al., 2024). Artificial intelligence (AI) and machine learning models are increasingly being integrated with sensor data to provide precise predictions and automated control of water quality, improving operational decision-making and efficiency (Lowe et al., 2022). For example, hybrid prediction models and fuzzy comprehensive evaluation methods help optimize water treatment and management strategies (Yaseen et al., 2018). Remote sensing technologies, including satellite monitoring, allow large-scale assessment of water color, transparency, and pollution levels, contributing to better ecosystem management (Adjovu et al., 2023).

3.3. Data management, robotics and Artificial Intelligence

Smart aquaculture involves integrating multiple smart devices within a specially designed environment to monitor cultured parameters in real time and make automatic decisions based on the data collected (Sharma & Kumar, 2021). It represents a modern production mode characterized by remote control and automation achieved through the application of technologies such as IoT, big data, artificial intelligence, 5G, cloud computing, and robotics. Additionally, smart aquaculture employs robotics to manage facilities, equipment, and machinery, enabling efficient operation of the entire system to ensure successful production (Kassem et al., 2021). Robotics and Drones are increasingly used for tasks such as underwater inspection, tank cleaning, harvesting, and surveillance of large farming areas. These technologies minimize manual labor, reduce human error, and enable precise management of aquatic stocks while ensuring minimal disruption to the animals (bogue, 2023).

Data Management and Artificial Intelligence (AI) platforms collect and analyze vast amounts of data from sensors and automated systems (Himeur et al., 2023). AI-driven analytics optimize feeding schedules, predict disease outbreaks, and support decision-making processes to maximize yield and sustainability (Ali et al., 2025). Integration of these digital tools enables smart farming practices, enhancing operational efficiency and environmental responsibility. The application of artificial intelligence (AI) in aquaculture encompasses a diverse array of technologies, including machine learning (ML), computer vision (CV), and data-driven decision-making systems (Chai et al., 2023). ML models are also used to predict and optimize the flow of products through the supply chain, ensuring timely delivery while reducing waste (Su & Huang, 2023). These technologies collectively enhance operational efficiency by enabling automated feeding, precise monitoring of fish growth and health, and real-time disease detection. By leveraging AI, farms can reduce production costs through optimized resource allocation and minimized waste. Moreover, AI-driven analytics support sustainable practices by improving water quality management and reducing environmental impacts (Zhao et al., 2021).

4. Benefits of Technological Integration

The integration of advanced technologies in aquaculture has brought about transformative benefits across multiple dimensions of production. Enhanced productivity and yield quality are achieved through precise, real-time monitoring of critical water quality parameters such as dissolved oxygen, pH, temperature, and ammonia levels, enabling optimal environmental conditions for aquatic species growth (Vettom et al., 2024). This continuous monitoring is facilitated by IoT-based sensor networks that collect and transmit data, allowing for timely interventions to prevent stress and disease in farmed fish. IoT systems also facilitate efficient resource management by automating feed delivery and regulating water and energy use, which reduces waste and minimizes environmental impact (Jagtap et al., 2021). Islam et al. (2022) proposed an IoT framework for real-time monitoring of aquatic environments by utilizing Arduino microcontrollers alongside various sensors. Their system collects data on critical water quality parameters such as pH, temperature, and turbidity to ensure optimal conditions in fish farming. Similarly, Arafat et al. (2020) developed a monitoring system based on experimental data gathered directly from a fishpond, employing respective sensors to measure parameters including temperature, pH, and turbidity for effective environmental monitoring. Early disease detection through continuous health monitoring helps prevent large-scale outbreaks, safeguarding fish populations and stabilizing production (Aly et al., 2024). Furthermore, IoT-generated data supports informed, proactive decision-making, enhancing operational efficiency and promoting sustainable farming practices. Economically, IoT integration lowers labor costs, improves worker safety by minimizing manual interventions, and increases profitability through optimized production (Shahab et al., 2024). Resource efficiency and environmental sustainability are significantly improved as automated systems optimize feed usage, minimize water and energy consumption, and reduce waste discharge, thus mitigating the ecological footprint of aquaculture operations (Liu et al., 2024). Moreover, technological integration reduces labor costs by automating routine tasks such as feeding and water quality checks, which not only decreases operational expenses but also enhance worker safety by limiting human exposure to hazardous or strenuous conditions (Ragab et al., 2025). AI-powered feeding systems, such as those developed by eFishery and GoSmart, offer affordable automation by monitoring fish hunger and environmental conditions to provide optimal feed amounts (Gokulnath et al., 2024). This reduces feed costs by up to 20%, limits waste, and improves fish health, making it an accessible option for small farms with limited resources (Munguti et al., 2021). The availability of comprehensive, real-time data through integrated platforms supports proactive and informed decision-making, enabling managers to anticipate and respond more effectively to environmental fluctuations, disease outbreaks, and other challenges (Mishra & Mishra, 2024).

Table 1. Benefits of technological integration

Benefit	Description	References
Enhanced Productivity	Real-time monitoring and automated control of water quality and feeding improve growth and yield.	Luna et al., (2016); Zuhaer et al., (2025)
Resource Efficiency	Technologies optimize feed usage, water, and energy consumption, reducing waste and costs.	Ramanathan et al., (2023)
Environmental Sustainability	Minimizing environmental impact through precise monitoring and controlling discharge parameters.	Kocer & Sevgili, (2014); Zuhaer et al., (2025)
Disease Monitoring and Prevention	Early detection and tracking of fish health help reduce mortality and avoid outbreaks.	Assefa & Abunna, (2018)
Cost Reduction and Labor Savings	Automation cuts down manual labor demands, lowering operational costs and improving worker safety.	Ragab et al., (2025)
Data-Driven Decision Making	Continuous data collection and analytics support proactive management to improve farm efficiency.	Mishra & Mishra, (2024)
Improved Product Quality	Controlled environment promotes healthier fish, improving quality and marketability.	Speranza et al., (2021)

5. Challenges and Future Perspectives

The main challenges in aquaculture include high production costs, disease outbreaks, environmental impacts, and reliance on unsustainable feed sources (Ruben et al., 2025). Future aquaculture requires focused research on advanced production systems like recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA) to improve resource use, productivity, and environmental sustainability. Despite economic challenges such as high costs, investment needs, and sludge management, innovations in bio-based treatments, renewable energy integration, and cost-effective filtration, including microalgae systems, can help balance economics with eco-friendly practices. Cooperative investments will ease financial pressures (Zhang et al., 2024). Addressing disease threats through enhanced surveillance, rapid diagnostics, effective vaccines, and biosecurity is critical, especially with emerging infections in various fish species posing risks to production (Aly et al., 2024). Developing disease-resistant strains via selective breeding and genetic engineering tailored to conditions is essential (Megahed, 2020). Sustainable feed development must reduce reliance on wild fish by exploring plant-based proteins and microbial biomass, optimizing formulations for better nutrition and lower environmental impacts (Dekari et al., 2024b). Adoption of emerging technologies like automation, AI, and IoT can allow real-time monitoring and efficient management, boosting productivity and sustainability. At last, effective collaboration among researchers, industry stakeholders, and policymakers is essential for the sustainable growth of aquaculture

(Das et al., 2022). By working together, research institutions, private companies, and government bodies can promote knowledge exchange, encourage the adoption of new technologies, and develop supportive policies and regulations. Such cooperation will foster innovation, generate job opportunities, and contribute to the long-term sustainability of the aquaculture industry.

6. Conclusion

The aquaculture industry is undergoing a profound transformation driven by cutting-edge technological innovations and automation, which are rewriting traditional paradigms of seafood production. Key advancements such as Recirculating Aquaculture Systems (RAS), precision aquaculture with IoT sensors and artificial intelligence, autonomous underwater vehicles, and digital twin models are enabling farmers to achieve unprecedented control over environmental variables, enhance biosecurity, and optimize feed and resource utilization. These technologies reduce water consumption, lower pollution, and improve fish health, thereby fostering sustainability while increasing operational efficiency. Moreover, integrated systems such as Integrated Multi-Trophic Aquaculture (IMTA), aquaponics, and biofloc technology introduce circular resource use, improving ecosystem balance and diversifying production outputs. Automation through robotics and AI-driven monitoring further reduces human labor and error, enabling real-time data-driven decision-making that enhances productivity and product quality. As global demand for seafood rises amid environmental and resource constraints, these innovations provide viable solutions to boost production capacity sustainably (Henriksson et al., 2021). The convergence of digital connectivity, sensor networks, and autonomous operations is paving the way for aquaculture to transition from labor-intensive, geographically limited systems to scalable, precision-managed farms with significantly reduced ecological footprints. In sum, the future of aquaculture lies in smart, automated, and environmentally integrated systems that can meet the dual challenges of feeding a growing global population and protecting aquatic ecosystems. This chapter highlights the critical innovations leading this revolution and underscores the necessity of ongoing research, development, and investment to harness the full potential of technology-driven aquaculture.

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CHAPTER VII

INTEGRATED MULTI-TROPHIC AQUACULTURE APPROACHES

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Introduction

Integrated Multi-Trophic Aquaculture (IMTA) is an innovative aquaculture system that combines the cultivation of species from different trophic levels within the same environment (Azhar & Memiş, 2023). By integrating organisms such as fish, shellfish, and seaweeds, IMTA creates a balanced ecosystem where the by-products (e.g., waste nutrients) from one species serve as inputs or nutrients for another. This effectively closes nutrient loops, enhances resource use efficiency, and mitigates environmental impacts associated with conventional monoculture practices (Rusco et al., 2024). The goal of Integrated Multi-Trophic Aquaculture (IMTA) is to establish balanced systems that promote environmental sustainability through biomitigation, ensure economic stability by diversifying products and reducing risks, and achieve social acceptability by implementing best management practices (Ghosh et al., 2025). Currently, IMTA stands out as a suitable approach for developing coastal aquaculture systems that are both economically viable and socially beneficial (Hossain et al., 2022).

The concept of IMTA emerged in the late 20th century as a response to the environmental challenges of traditional aquaculture, including water pollution and ecosystem degradation. Over recent decades, aquaculture's share of global fish production increased to 82.1 million tonnes (46%) out of 179 million tonnes in 2020, and is expected to reach 53% by 2030 (F.A.O. 2020). Early research and pilot projects in countries such as Asia, Canada and China demonstrated the potential of IMTA to enhance sustainability by mimicking natural food webs and improving ecosystem resilience. Over the past few decades, IMTA has gained global attention and has been adopted in a variety of contexts, from small-scale coastal farms to commercial operations worldwide (Sukhdhane et al., 2018). IMTA holds significant importance for sustainable aquaculture by offering ecological, economic, and social benefits. Ecologically, it reduces nutrient loading and enhances water quality through biological filtration (Khanjani et al., 2022). Economically, it diversifies farm production, reducing financial risks and increasing profits. Socially, it promotes responsible farming practices, supporting coastal communities and contributing to food security (Alam et al., 2024). Thus, IMTA represents a promising path towards environmentally sound and economically viable aquaculture for the future.

1. Principles and Components of IMTA

Integrated Multitrophic Aquaculture (IMTA) is founded on ecological principles that integrate species from different trophic levels, creating a synergistic system that efficiently recycles nutrients and mimics natural aquatic ecosystems (Choudhary et al., 2025). The core idea is to transform the metabolic waste and uneaten feed from fed species into valuable inputs for extractive species, thereby closing the loop of nutrient cycling and reducing environmental impact (Hasan & Lateef, 2024).

IMTA systems typically involve at least three functional groups:

- **Fed Species:** These are primarily finfish (e.g., salmon, tilapia) or crustaceans (e.g., shrimp) that are cultivated with external feed. Their feeding and metabolic activities produce organic and inorganic wastes, including uneaten feed, feces, and dissolved nutrients, which can pollute the environment if unmanaged (De Silva et al., 2009; Dauda et al., 2019).
- **Organic Extractive Species:** These species, such as filter-feeding bivalves (mussels, oysters, clams) and deposit feeders (sea cucumbers, sea urchins), consume organic particulates like feces and uneaten feed that settle out of the water column. They help purify water and convert waste into harvestable biomass (Grosso et al., 2023).
- **Inorganic Extractive Species:** Mainly macroalgae or seaweeds (e.g., Ulva, Gracilaria, Saccharina), these organisms absorb dissolved inorganic nutrients such as nitrogen and phosphorus compounds from the water. They act as living biofilters, mitigating risks of eutrophication and improving water quality (Kang et al., 2021; Naskar et al., 2023).

2.1 Factors determine the compatible species combinations (finfish, shellfish, seaweeds, etc.)

The selection of species for IMTA requires careful consideration of their ecological role, adaptability to farming conditions, biomitigation efficiency, and economic value. Species must actively complement each other and thrive in a shared environment, collaborating in resource use and sustainability (Fig.1) (Khanjani et al., 2022). Successful IMTA relies on pairing species whose biological processes and nutrient demands align well. For example, finfish such as salmon are commonly co-cultured with shellfish like mussels and seaweeds such as kelp (Zhu et al., 2025). The finfish produce nitrogen-rich waste that seaweed can uptake, while shellfish filter particulate matter, creating a balanced nutrient cycling chain. This combination not only reduces pollution but also yields diverse products, enhancing farm profitability. Other combinations might include shrimp with sea cucumbers and seaweed, or cod with oysters and Gracilaria (Kim et al., 2022).

IMTA systems redefine aquaculture waste as resources by orchestrating nutrient cycling pathways:

- Solid organic wastes and particulates from fed species are captured by organic extractive species (Cranford et al., 2013).
- Dissolved inorganic nutrients such as ammonium and phosphate are absorbed by inorganic extractive species like seaweeds (Naskar et al., 2023).

This process mitigates nutrient accumulation in the aquatic environment, lowering risks of oxygen depletion and algal blooms. Additionally, IMTA promotes ecosystem services such as improved water clarity, habitat complexity, and biodiversity enhancement. Diverse species assemblages create more resilient and stable farming ecosystems, reducing disease outbreaks and bolstering environmental sustainability (Hossain et al., 2022; Ruiz-Vanoye et al., 2025).

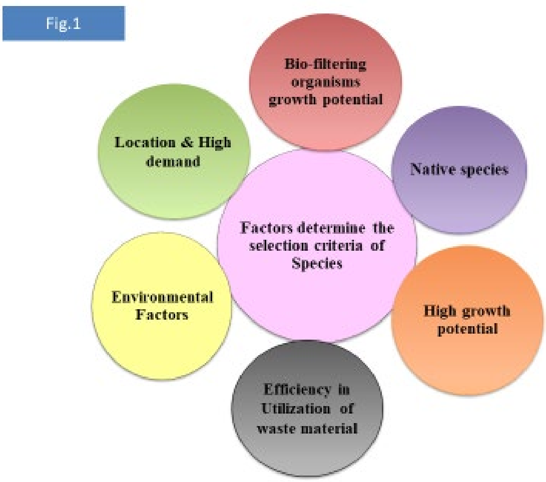

Figure 1. species must actively complement each other and thrive in a shared environment. (Viji, 2015).

2. IMTA System Design and Configurations

Integrated Multi-Trophic Aquaculture (IMTA) systems are designed with flexibility to operate in various environments, primarily categorized as open-water and land-based systems. Each system type has specific configurations and operational considerations that influence nutrient cycling, species interactions, and overall sustainability (Choudhary et al., 2025).

Table.1 IMTA system design and configurations

Configuration Aspect	Description	Key Features and Benefits	References
Open-Water IMTA	Utilizes natural water bodies such as oceans, seas, or lakes where aquaculture infrastructure is anchored or moored.	Leverages natural water flow for nutrient dispersal, interaction with environment; suitable for marine species and larger-scale operations	Nguyen & Wang, (2024)
Land-Based IMTA	Cultivation in controlled environments such as tanks, raceways, or ponds on land; often integrates RAS technologies.	Offers better environmental control (water quality, feeding); reduced risk of escape and environmental contamination; suitable for freshwater and marine species	Walker, (2018)
RAS Integration in IMTA	Combines recirculating aquaculture systems with IMTA by reusing and filtering water in a closed loop, integrating multiple trophic levels.	Improves nutrient recycling efficiency, minimizes water use and waste discharge; enables modular, customizable system design	Zimmermann et al., (2023)
Spatial and Temporal Arrangements	Strategic placement and timing of species within IMTA systems to optimize nutrient flow and species interactions.	Enhances efficiency through compatible species placement (e.g., feeder fish upstream, extractive species downstream), and scheduling crop rotation or harvest for balanced ecosystem dynamics	Nederlof et al., (2022), Shah et al., 2017

3.1 Open-Water vs. Land-Based IMTA Systems

Open-water IMTA systems are typically located in marine or freshwater bodies, where multiple species are co-cultivated in natural aquatic environments such as coastal waters or lakes. This system leverages natural water currents to facilitate the transfer of nutrients and wastes between trophic levels (Bablee et al., 2024). Most open-water Integrated Multi-Trophic Aquaculture (IMTA) sites typically fall into one of three categories: (i) locations where co-cultured species are added onto an existing commercial-scale aquaculture operation (Chopin et al., 2012); (ii) custom-designed IMTA farms specifically developed for integrated polyculture systems (Reid et al., 2017) and (iii) incidental IMTA that occurs simply due to the proximity of different farms cultivating different species nearby, resulting in unintentional integration. It has also been suggested that IMTA should be considered broadly in the context of an Integrated Coastal Area Management (ICAM) strategy (Chopin, 2017). Assessment of open-water IMTA is more complex due to the ‘leaky’ nature and rapid dilution of nutrients in these systems. As open-water aquaculture occurs in natural ecosystems that are inherently dynamic, the dissolved nutrient load may disappear quickly (‘ghost nutrients’) due to rapid assimilation by the food web (Reid et al., 2020). Typically, finfish cages are paired with shellfish and seaweed positioned strategically to capture organic particles and dissolved nutrients released by fed species. The reliance on natural water flow makes it cost-effective but also less controllable and subject to environmental variability (Callier et al., 2018).

In contrast, Land-based IMTA is inherently more efficient in nutrient utilization than open water IMTA. Land-based IMTA systems involve contained environments such as tanks, ponds, or raceways, often incorporating Recirculating Aquaculture Systems (RAS) technology. Land-based systems optimize nutrient utilization through closed containment, minimizing loss and maximizing access via multiple water passages (Angel et al., 2019). Land-based IMTA allows greater control over environmental parameters including water quality, temperature, and nutrient concentrations (Zhu et al., 2025). Water is recirculated and treated through integrated filtration and biofiltration components, reducing water use and enabling intensive farming practices. The land-based approach aids in meeting sustainability and biosecurity goals by minimizing environmental discharge and enhancing waste management (Ahmed, 2024).

3.2 Recirculating Aquaculture Systems (RAS) Integration

The integration of IMTA with RAS is an emerging innovative approach that combines the benefits of multi-trophic cultivation with advanced water treatment technologies. RAS involves the continuous reuse of water through mechanical and biological filtration, enabling the rearing of aquatic species in a highly controlled environment (Holan et al., 2020). When IMTA is incorporated into RAS, waste products from fed species are efficiently converted by extractive species (e.g., filter feeders, seaweeds), which contributes to nutrient recycling within the system (Nederlof et al., 2022). This integration facilitates the optimization of feed utilization, water conservation, and waste bioremediation. Furthermore, modular and flexible designs allow tailored environmental conditions for each species within the polyculture, increasing productivity while reducing ecological footprints. Such land-based IMTA-RAS systems demonstrate promising potential for sustainable, zero-discharge aquaculture (Thomas et al., 2021).

3.3 Spatial and Temporal Arrangements

Spatially, IMTA systems arrange species in configurations that maximize trophic interactions and nutrient uptake. There are several variants of IMTA, such as freshwater aquaculture/agriculture systems incidental IMTA and open-water marine systems (Reid et al., 2020). Some open-water IMTA models modify existing ecosystem models that couple physical (hydrodynamics) and biogeochemical components. These ecosystem type models are most developed for shellfish aquaculture and/or aquaculture and coastal management (Reid et al., 2011). In open-water configurations, placement follows trophic cascades: fed species located upstream or higher in the water column, organic extractive species positioned to intercept settling particulates below, and inorganic extractive species often arranged to absorb dissolved nutrients downstream or nearby (Grosso et al., 2023). In land-based systems, spatial design is modular; tanks or compartments for each species are connected to allow controlled flow of water and nutrients through the system (Tian & Dong, 2023).

Temporal arrangements in IMTA refer to the timing and cycling of species cultivation and harvest. Species with differing growth rates and life cycles are managed to maintain continuous nutrient recycling for example, fast-growing seaweed can be harvested seasonally to prevent nutrient saturation while slower-growing shellfish or finfish are cultivated over extended periods (Checa et al., 2024). Coordinated temporal management enhances system stability, biomass productivity, and economic returns. Careful design and layout of IMTA systems, whether open water or land-based, along with RAS technologies and strategic spatio-temporal planning, are crucial for successful and sustainable aquaculture (Nissar et al., 2023).

3. Ecological and Environmental Benefits

IMTA offers substantial ecological and environmental advantages by effectively reducing waste nutrients, enhancing water quality through biofiltration, and boosting habitat complexity and biodiversity (Khanjani et al., 2022).

4.1. Waste Nutrient Reduction and Biofiltration

In IMTA systems, organic extractive species are used to reduce the nutrient load of the water acting at different trophic levels according to the type of organic matter produced by fish farms. Deposit feeders like polychaetes, sea cucumbers, and sea urchins consume larger organic particles, such as uneaten food and feces that settle at the bottom of cages. Filter feeders such as mussels, oysters, scallops, and sponges filter finer suspended particles from the water column (Nissar et al., 2023). IMTA harnesses the synergistic relationships among species from different trophic levels to recycle nutrients effectively. In IMTA farming, seaweed serves as primary producers, oxygenating the water, reducing CO_2 and ammonia, and absorbing excess nutrients. Fed species like finfish release substantial organic and inorganic wastes that, in monoculture, would contribute to nutrient pollution (Verdian et al., 2020). In IMTA, extractive species such as shellfish and seaweeds capture these wastes by filtering particulates and absorbing dissolved nutrients, respectively. This bio-filtration process markedly reduces nutrient discharge into the environment, mitigating risks of eutrophication and hypoxia (Choudhary et al., 20250. For example, kelp and mussels grown alongside salmon utilize nitrogenous wastes and organic matter, leading to improved ecological balance in coastal waters (Ueland, 2022).

By converting waste nutrients into biomass, IMTA improves water clarity and reduces concentrations of harmful compounds like ammonia and phosphates (Ghosh et al., 2025). The biological uptake by extractive species maintains nutrient levels within safe thresholds, supporting healthier aquatic habitats and cultured organisms (Bernhardt et al., 2021). This natural water purification mechanism surpasses conventional filtration by simultaneously providing biomass for harvest, enhancing system sustainability. Cleaner water in IMTA systems also supports adjacent fisheries and helps protect sensitive marine habitats (Resende et al., 2021).

4.2 Habitat Enhancement and Biodiversity Promotion

IMTA promotes biodiversity by mimicking natural ecosystems, fostering resilient and stable environments (Hossain et al., 2022). The structural complexity added by seaweed beds and shellfish reefs creates habitats for various marine species, encouraging ecological interactions and enhancing local biodiversity. This habitat complexity contributes to ecosystem services such as disease regulation, nutrient cycling, and increased ecosystem productivity (Cotas et al., 2023). Marine macroalgae, an essential IMTA component, not only sequester carbon and nutrients but also support diverse communities, reinforcing ecosystem health (Liu et al., 2022). In sum, IMTA's efficient nutrient recycling, natural biofiltration, and ecological structuring support environmental sustainability and contribute to resilient aquaculture ecosystems. This integrated approach reduces aquaculture's ecological footprint, enhances water quality, and fosters biodiversity, making it a promising model for sustainable aquaculture worldwide (Khanjani et al., 2022).

5. Economic and social aspects

Integrated Multi-Trophic Aquaculture (IMTA) offers notable economic and social advantages that extend beyond conventional aquaculture practices, making it an attractive model from both financial and community perspectives. One of the key economic strengths of IMTA is its ability to diversify farm outputs by cultivating multiple species across different trophic levels within the same system (Rusco et al., 2024). This diversification not only creates a variety of products such as finfish, shellfish, and seaweeds but also opens access to differentiated markets, including health foods, nutraceuticals, and cosmetics (Calado et al., 2018). By producing a broader range of aquaculture products, IMTA farms can tap into premium markets, sometimes commanding price premiums due to the environmental sustainability and quality of IMTA products. This multi-product approach reduces dependency on a single crop and buffers farmers against market fluctuations or disease outbreaks, enhancing overall economic resilience (Beg et al., 2024). Though IMTA systems may face higher initial capital and operational costs due to their complexity and need for specialized management, cost-benefit analyses have demonstrated that IMTA can improve long-term profitability (Sergio et al., 2025). Studies indicate that IMTA farms often achieve higher net present values (NPV) than monoculture farms by benefiting from reduced risks and diversified income streams (Knowler et al., 2020). The operational costs are sometimes offset by savings from ecosystem services such as natural bio-filtration, which reduces water treatment expenses. Additionally, the spread of administrative and marketing costs over multiple products improves economic efficiency. Importantly, IMTA's increased resilience to environmental and market variability adds to its long-term economic sustainability (Shah et al., 2021).

Integrated Multi-Trophic Aquaculture (IMTA) not only offers environmental advantages but also delivers significant social and economic benefits. The interconnected spheres of sustainability social, economic, and environmental (Biswas et al., 2020) are widely recognized (Fig.2). This framework applies to Integrated Multi-Trophic Aquaculture (IMTA) as well as other resource management approaches (Yang, 2019). For more than twenty years, it has been proposed that IMTA enhances sustainability by mitigating the environmental impacts of intensive aquaculture and providing economic advantages to producers through product diversification, accelerated production cycles, and premium pricing of IMTA products (Alexander et al., 2016). By allowing farmers to diversify their production, IMTA enables the harvesting and marketing of multiple species, which enhances profitability while reducing risks associated with market fluctuations. This diversification provides farmers with multiple revenue streams, helping them maintain economic stability even when demand for a particular species decline (Hossain et al., 2022).

In addition to direct financial benefits, IMTA promotes a healthier aquatic environment with cleaner water and a more balanced ecosystem (Rusco et al., 2024). These improved conditions support local economies reliant on natural resources by sustaining fisheries and boosting tourism opportunities. Cleaner waters and vibrant ecosystems attract visitors and enhance community livelihoods tied to coastal and marine resources (Dash & Balamurugan, 2024). IMTA positively influences coastal and rural communities by generating new employment and skills development opportunities in areas such as specialized species cultivation and system management. The diversity of cultured species translates into varied income sources, supporting local economies and improving livelihoods (Zhu et al., 2025). Cleaner, healthier aquatic environments resulting from IMTA practices also support traditional fisheries and tourism sectors, fostering broader socio-economic benefits. Furthermore, by promoting environmentally responsible practices, IMTA enhances the social acceptability of aquaculture, potentially leading to stronger societal support and policy backing. This inclusiveness aligns with sustainable development goals, balancing economic growth with environmental stewardship and community well-being (Dash & Balamurugan, 2024).

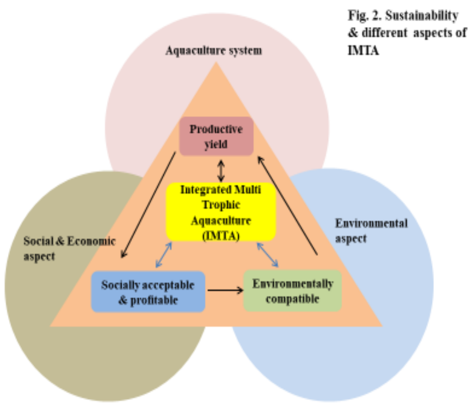

Figure 2. The interconnected spheres of sustainability social, economic, and environment (Choudhary et al., 2025)

6. Technological Innovations and Monitoring Tools

Technological innovations have become pivotal in advancing Integrated Multi-Trophic Aquaculture (IMTA), enabling more efficient management, enhanced sustainability, and optimized productivity through the use of IoT, sensors, automation, and data-driven decision-making (Ruiz-Vanoye et al., 2025).

6.1 Use of IoT, Sensors, and Automation in IMTA

The incorporation of Internet of Things (IoT) technologies and sensor networks in IMTA allows for real-time monitoring and control of critical parameters such as temperature, dissolved oxygen, pH, salinity, and nutrient concentrations (Ruiz-Vanoye et al., 2025). Advanced sensors placed strategically within different culture units can continuously collect environmental and biological data, offering precise insights into the health and growth of various species across trophic levels (Wang, 2024). Automation systems facilitate optimized feeding regimens, waste removal, and water circulation, reducing labor demands and minimizing human error. These technologies support dynamic adjustments to farming operations, maintaining system balance and improving yield while reducing environmental impacts (George & George, 2023). Water quality is central to IMTA success, given the interdependency of multiple species and their varied sensitivities. Sophisticated monitoring techniques, including optical sensors, fluorometers, and bio-indicators, enable early detection of water quality fluctuations or emerging disease threats (Barad et al., 2024). Non-invasive health assessment tools such as image analysis, behavior detection through computer vision, and molecular diagnostics help in continuous monitoring of stock health. This proactive monitoring is vital to prevent disease outbreaks and ensure optimal environmental conditions, which promote resilience and productivity within IMTA ecosystems (Alotaibi et al., 2021).

Harnessing data analytics, artificial intelligence (AI), and machine learning models, precision aquaculture enables informed decision-making in IMTA management. By integrating multi-source data streams, farmers can forecast growth rates, optimize species ratios, predict potential stressors, and devise adaptive management strategies. Decision support systems powered by real-time data facilitate resource-efficient production, reducing feed waste and energy consumption. These technologies also help fine-tune harvest timings and improve market readiness, enhancing economic outcomes (Hu et al., 2023). In summary, technological innovations, through IoT, sensor integration, health monitoring tools, and data-driven analytics, support IMTA's goal of sustainable, efficient, and resilient aquaculture. These tools not only increase productivity and environmental stewardship but also empower farmers with advanced capabilities for adaptive system management.

Table 2. Technological innovations and monitoring tools

Technological Innovation	**Description**	**Application in IMTA**	**References**
IoT-enabled multi-sensor systems	Wireless sensors to monitor water quality parameters such as temperature, pH, dissolved oxygen, and turbidity	Continuous real-time monitoring of water quality in IMTA to ensure optimal conditions for multiple species	Rejeb et al., (2025)
Data Aggregator Systems (DAS)	Gateways that interface deployed sensors with cloud platforms for data aggregation and analysis	Supports eco-intensification by enabling data-driven management of IMTA sites, addressing connectivity and power limitations	Misbahuddin et al., (2025)
IoT-based monitoring and control	Systems integrating IoT with renewable energy (solar) for autonomous control of aquaculture environments	Facilitates sustainable urban and off-grid IMTA operations by automating control of feeding, aeration, and water quality	Dewi et al., (2025)
AI and predictive analytics	Integration of machine learning algorithms with IoT sensor data for predictive monitoring and decision support	Enhances shrimp and fish farming efficiency by predicting adverse conditions and optimizing resource use in IMTA	Rosati et al., (2023); Ahmed et al., (2024)

7. Challenges and Limitations

Integrated Multi-Trophic Aquaculture (IMTA), despite its numerous benefits, faces several challenges and limitations that complicate its widespread adoption. Managing multiple species simultaneously in IMTA systems requires careful compatibility assessments to ensure co-cultured organisms can thrive together without detrimental interactions (Zhu et al., 2025). Differences in environmental preferences, feeding habits, and disease susceptibility demand precise coordination. Disease management becomes complex, as pathogens or parasites may transfer between species or proliferate under stressful conditions. The use of antibiotics, chemicals, or hormones to control diseases can have cascading effects on other trophic levels and surrounding ecosystems, necessitating integrated health management strategies to maintain balanced system health (Singh et al., 2024). While IMTA aims to reduce nutrient pollution, nearshore farms can still increase pressure on local ecosystems, particularly in areas with limited flushing capacity. Nutrient build-ups can cause harmful algal blooms, oxygen depletion, and disruptions to phytoplankton communities (Buck et al., 2018). Regulatory frameworks for IMTA are still developing in many regions, presenting hurdles related to site leasing, environmental impact assessments, and licensing. Fragmented or unclear policies, combined with political influences and competing coastal uses, hamper systematic IMTA implementation and enforcement of best practices. Effective coastal zone management and integrated policies are critical to mitigate environmental risks and support sustainable IMTA expansion (Falconer et al., 2023). IMTA systems require higher initial capital investments and operational expertise compared to monoculture systems. The complexity of managing diverse species demands specialized knowledge, training, and labor, increasing operational costs. Market development for extractive species and by-products remains a challenge in some regions, impacting profitability. Furthermore, spatial variability in hydrodynamics and ecosystem productivity influences IMTA outcomes, complicating standardized system design and scale-up. These technical and economic challenges limit adoption, particularly among small or resource-limited farmers, emphasizing the need for supportive financial instruments, research, and extension services to unlock IMTA's full potential (Tran et al., 2023).

8. Future perspectives and research directions

Future perspectives and research directions in Integrated Multi-Trophic Aquaculture (IMTA) focus on expanding species selection, integrating with circular bioeconomy and blue growth strategies, and leveraging advanced genetic and molecular tools for system optimization (Ruiz-Vanoye et al., 2025). Expanding the repertoire of species used in IMTA is vital to optimizing ecosystem functions and increasing economic outputs. Emerging species include marine sponges, deposit feeders, and novel macroalgae, which offer unique nutrient cycling or bioremediation potentials (Amato et al., 2024). Better understanding and harnessing complex trophic interactions among fed species, organic extractive species (like shellfish), and inorganic extractive species (such as seaweeds) can improve system stability and productivity. Strategic species combinations tailored to local environmental conditions promote sustainable ecosystem services and diversified markets. IMTA aligns well with circular bioeconomy principles by turning aquaculture wastes into resources, thus minimizing environmental footprints and supporting sustainable resource use. It promotes blue growth by enhancing aquaculture productivity while restoring or maintaining ecosystem health. Future research aims to embed IMTA more deeply into value chains where biomass from all trophic levels is valorized, including uses in bioenergy, pharmaceuticals, animal feed, and fertilizers. This integration fosters closed-loop systems contributing to climate resilience, biodiversity conservation, and sustainable livelihoods. Genetic and genomic developments, including selective breeding, genomic selection, and CRISPR gene editing, offer new ways to enhance IMTA by improving growth rate, disease resistance, and environmental tolerance in crop species (Bigini et al., 2021). Molecular tools also enable precise monitoring of species health and environmental conditions through transcriptomics and metabolomics, facilitating early detection of stress or disease. Combining these tools with bioinformatics and systems biology can optimize species interactions and nutrient cycling, ultimately boosting productivity and sustainability (Satrio et al., 2024).

9. Conclusion

Integrated Multi-Trophic Aquaculture (IMTA) offers a transformative approach to aquaculture by integrating multiple species from different trophic levels to create balanced, sustainable systems that provide ecological, economic, and social benefits. The key advantages include reducing environmental impacts through waste recycling and biofiltration, improving water quality, enhancing habitat complexity, and promoting biodiversity (Chen et al., 2023). Economically, IMTA supports product diversification which reduces market risks and improves profitability. Socially, it generates employment and strengthens community livelihoods, especially in coastal and rural areas. However, IMTA also faces challenges such as species compatibility and complexities in disease management, environmental threats including local nutrient depletion, evolving regulatory frameworks, and economic/technical barriers, including high capital costs and the need for specialized knowledge. Overcoming these challenges requires integrated management, supportive policies, and capacity building. For sustainable adoption, strategic recommendations include promoting research on species interactions and system design, supporting market development for all trophic products, encouraging collaboration among farmers and stakeholders, and integrating IMTA within circular bioeconomy and blue growth frameworks. Advances in genetic and molecular tools should be leveraged to optimize species performance and health monitoring. Policies must foster adaptive governance and streamline regulatory processes to facilitate technological innovation and economic viability. In conclusion, with the right investments in technology, research, policy, and community engagement, IMTA holds great promise as a sustainable and resilient aquaculture model capable of meeting global food security and environmental conservation goals.

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CHAPTER VIII

POLICY, REGULATION, AND CERTIFICATION FOR SUSTAINABLE AQUACULTURE

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Introduction

Aquaculture has succeeded in fisheries as the primary source of seafood for people worldwide due to its quick growth. Aquaculture is a relatively new contribution to the world food supply chain. With an annual growth rate of 9.58% from 1990 to 2018, aquaculture is the world's rapidly growing food-producing sector, reaching 114.5 million tons of gross weight in 2018 with a $263.6 billion farm-gate sale value. However, aquaculture has ability to support public and ecological health, subsistence and food security (FAO, 2022).

Aquaculture industry is facing several significant obstacles. The environment is one hurdle. Aquaculture can be seen to contribute positively to the environment overall by easing the strain on wild fish supplies, but it can also have a number of detrimental effects on the ecosystem at the local level. These include the possibility of genetic contamination due to escapes, the spread of illness in fish to wild stocks, and pollution from aquaculture farms, notably from toxins and waste products (Borriello, 2024).

The water plant risk and aquatic animal's illness is another significant danger to the sector's continued existence. Under these conditions, the absence of a suitable policy climate that supports aquaculture can be a significant barrier to the sector's expansion in developing as well as developed nations.

Effective and flexible governance that incorporates the fundamental values of accountability, efficiency, predictability and equity makes long-term sustainability achievable. Several nations have improved aquaculture production over the last ten years by implementing legislation and changing administration through implementation plans, and stakeholders have benefited from these improvements throughout the value chain (Alexander et al., 2015).

The sustained shift which is, the systemic adjustments required for individuals and societies to decrease their overall negative ecological effects and to move from unproductive to more sustainable practices is required for further increase of aquaculture production. Law can help bring about structural modifications, but a shift to sustainability requires a number of prerequisites that transcend behind the law, including governance, investment and innovation (Johnstone and Newell, 2018).

The government could assist the industry by promoting the involvement of non-governmental organizations (NGOs) and the private sector. Therefore, initiatives that maintain a balance between increased production and environmental protection should be part of governance. The implementation of a regulatory policy framework or informal agreements that involve local associations, private sectors, advocacy groups and stakeholders in making decision to achieve a shared goal, like executing the public's services or programs, is known as governance. It is essentially about relationships, power, and accountability: who makes decisions, that is influential, as well as those who make decisions are held responsible (Abate et al., 2018).

There are long-term advantages if the aqua farming sector is made more environmentally friendly. Therefore, policymakers should focus on export promotion and support the development of marketing strategies, identification and certification of products, authenticity, laws and regulations for global trade (e.g., tariff rates), accessibility and reliability of information on markets available to producers/exporters, processing, preservation, and transport technologies, and the institutional development of marketing organizations (Bush et al., 2013).

The aquaculture industry has contributed to rise in the importance of sustainable certification, giving rise to numerous programs with different requirements. A growing emphasis on sustainability by governments, nonprofit organizations, consumers and corporations has led to the proliferation of sustainability certifications across many sectors. Aquaculture businesses can earn volunteer certificates under these commercial regulatory efforts by proving they meet a set of requirements, which are often evaluated by an external auditor. These certifications are meant to provide enhanced transparency, global equalization, as well as accountability in a market that is becoming more globalized (Busch, 2017).

The absence of preliminary information on the many aspects of resilience prior to the development of aquaculture facilities is one of the challenges in evaluating the relationship between local resilience and green aquaculture practices. The aim of this chapter is to investigate the legal, regulatory, and certification systems that govern sustainable aquaculture methods around the world to maintain social justice, environmental stewardship, and aquaculture's financial sustainability.

Policy Frameworks for Sustainable Aquaculture

Sustainable development policy framework gives a scalable approach offered by the aquaculture governance application to a predictive and evaluative method of assessing the effects of regulation on aquatic development. Each strategy or policy is developed with input from the community and stakeholders, and it is directed by the sustainability requirements and governance principles that are present in the aquaculture industry. Traditional fishery management, natural scientists and environmental organizations have been the main forces behind aquaculture rules and regulations. The development of aquaculture in any nation depends on four primary policy areas: trade policies, regulatory frameworks that provide social and environmental safety precautions, policies that promote aquaculture production chains, and governmental investments in infrastructure and research and development The importance of international as well as domestic value chains is a key component of the discourse around aquaculture policy, innovation, and expansion (Jolly et al., 2023).

NOAA (National Oceanic and Atmospheric Administration) has comprehensive research papers on the regulatory and legal barriers to growing shellfish aquaculture in the United States. Recently, the United States has engaged stakeholders in aquaculture. A working group on aquaculture, for instance, was established by the United States Department of Agriculture (USDA) to give the domestic aquaculture industry a forum to discuss how USDA might effectively support this farming community. Even though aquaculture has been supported by numerous governance initiatives in nations like Paraguay, Peru, and Colombia flaws still exist and prevent continued aquaculture development. Aquaculture has insufficient institutional and political significance in Latin America and the Caribbean (LAC), which leads to weak policies and little funding for the industry (Biga et al., 2020).

In the major Asian aquaculture-producing nations, legislative and administrative frameworks for the advancement of aquaculture have been established. Institutional mechanisms for enforcement and execution have also been built, together with pertinent policies, rules, regulations, and standards. Additionally, financial limitations and a lack of infrastructure, knowledge, or other essential inputs are two more obstacles to aquaculture that government policies may be able to help overcome (Ruff et al., 2019).

EU Aquaculture Legislation

Entrepreneurship and European policy for research and technical development activity seem to be the main drivers of the rapid growth of recirculating aquaculture systems. Aquaculture, fisheries and aquaculture products, processing, and the preservation, governance, and utilization of living aquatic resources are all covered under the EU's Common Fisheries Policy. Aquatic production throughout the European Union is growing at a far slower rate than the global average. The EU’s production has expanded by six percent since 2007 (Puszkarski & Śniadach, 2022).

A little over twenty percent of the shellfish and fish that are domestically provided to EU consumers are aquaculture services products produced in the EU. About 70,000 people are directly employed in this industry, which is composed of roughly 15,000 different types of firms. The Common Fisheries Policy Committee identified three priority areas in its 2019 guidance for potential strategies for the long-term advancement of EU aquaculture: ensuring sustainable growth through the optimization of licensing procedures, boosting EU aquaculture's competitiveness level. In 2019, the European Commission unveiled the European Green Deal program as a response to environmental and climatic concerns. This program lays forth policy measures to assist the EU in becoming climate neutral by 2050 and creating a competitive, resource-efficient, and technological economy. The 2030 Agenda for the United Nations Sustainable Development of Nations is intended to be implemented with the aid of the Green Deal. The primary goal of this initiative is to change the EU economy to create an economical viable future (Mente and Smaal, 2016).

Legal framework at the National and international level

The primary goals of the national mariculture policy are to adopt an environmentally sustainable approach to mariculture development, boost revenue, job growth, and entrepreneurial possibilities in a sustainable and responsible manner, and increase aquaculture output across the nation. The Pakistani government established the National Commission on Agriculture (NCA) in 1986. As a result, NCA put forth a comprehensive plan for 1988–2000. Maintaining self-sufficiency to increase the productivity of crops, forests, fisheries, and livestock was the commission's principal goal. Based on provincial to the federal level approach, there are suitable fisheries institutions; nevertheless, aquaculture and fisheries policies are not successfully executed because of a lack of coordination. Thus, guaranteeing aquaculture development, cooperation and assistance from the public and commercial sectors are crucial (Ignatius, 2023).

Three major organizations' regional policy frameworks supporting the development of aquaculture in Africa—the East Africa Community, the African Union Commission, and the Indian Ocean Rim Association—were examined for their attention to advantage exchange mechanisms and used as a standard to evaluate how well national policies aligned with the intended regional development objectives (Brugere et al., 2021). Experts have recognized increased aquaculture production as a key policy objective for the United States, which might be achieved by mariculture industrial expansion or intensified production in certain circumstances. Over the past ten years, aquatic spatial planning has become more popular in the US. In addition to the state-level marine plans that have been put into effect in Rhode Island, Oregon, Massachusetts, President Obama's 2010 executive action implementing a National Ocean Policy included a call for regional planning organizations to be in charge of creating waterfront and marine spatial plans for each of the nine geographic regions. It accomplished this by closely monitoring an expert-directed decision-making system and using data and analyses from consultants as well as industry sector to guide decisions. It sought to create tangible guidelines that can be used anywhere in the world (Lester et al., 2018).

Fisheries Management Projects

A basic legal foundation for all types of activity in the water bodies is provided by united nation convention on the law of sea (LOSC's), which was established in 1982. The LOSC's prelude clearly acknowledges its goal of advancing the preservation of aquatic creatures, particularly fisheries resources, and it created a fundamental framework for global collaboration in this area. The continued viability of ecosystem and fisheries through the Ministry of Marine Affairs and Fisheries of the Government of Indonesia believes that a systemic strategy for management of fisheries (SSMF) is the best option (Pomeroy et al., 2015). The Coral Reef Rehabilitation Program (COREMAP), Sustainable Ecosystem Advanced (SEA) Program, Arafura Timur Sea Ecosystem Action (ATSEA) Program, OCEANS, and Indonesia's ratification of the Port State Measures Agreement (PSMA) are some of the government-led initiatives that embrace the Ecosystem Approach to Fisheries Management (EAFM). The maintenance of sustainable fisheries is a top priority for the FAO, which is the main organization responsible for aquaculture fisheries management. The Code of Conduct for Responsible Fisheries, the Agreement on Port State Measures to Prevent, Deter and Eliminate IUU Fishing (PSMA), and a number of International Plan of Actions (IPOAs) pertaining to fishing issues, including the United Nations Action Plans for the Regulation of Fishing Capability and the worldwide Action Plans to Reduce, prevent and eradicate IUU Fishing (IPOA-IUU), are just a few of the numerous fishery regulations that it has developed and issued. The marine fishing resources have benefited greatly from these tools (Suncls and Cai, 2024).

Integrated and Coherent Aquaculture Policy Framework

It is challenging to maintain uniformity in policy and prevent unforeseen repercussions due to the complex policy framework, especially when possible trade-offs are not made clear. The relationship between China's declared fishery management objectives and subsidies and the governance features of small-scale aquaculture has also been examined in connection to policy coherence. Fishery policy formulation and reform and policies aimed at obtaining fish from overseas were examined in the European Union using uniformity in policy analysis. In Australia, coherent policies analysis has been applied to examine and enhance governance, such as when it comes to the marine migratory species. In particular, it might be necessary to modify certain provisions of the laws pertaining to food safety, fish health, and disease transmission (Alexander et al., 2020).

Planning and licensing for marine aquaculture

Although marine aquaculture has the potential to contribute more to the global food chain and offer significant ecosystem benefits, sustainable development requires the implementation of suitable planning, licensing, and regulatory frameworks Social acceptance of marine aquaculture also depends on good governance, yet in certain nations, aquaculture licensing has turned into a divisive social and regulatory problem. It is obvious that creating a strong and equitable licensing system with corresponding regulations is difficult but necessary given the complexity of aquaculture (Falconer et al., 2023).

The necessity of updating and streamlining the licensing procedures has been brought to light by recent national assessments in nations including Scotland England, and Ireland. The "green," "development," and recently suggested "eco-technology" licenses are all intended to promote the advancement in ecological technologies and lessen the detrimental effects of fish farming on the environment. The foundation for creating environmental regulations that spur technological advancement can be exemplified by the three different types of licenses (Osmundsen et al., 2022).

Climate change Adaptation Policies in fisheries and aquaculture

A significant number of EU fisheries and aquaculture legislative frameworks, including the Common Fisheries Policy (CFP), the Marine Strategy Framework Directive (MSFD), and the 2013 "Strategic guidelines for the sustainable development of EU aquaculture do not address climate change. Working relationships and active stakeholder participation have been highlighted as essential components of climate change adaptation. CAPs can be designed for aquaculture at any scale, from the farm, municipality, or local level to the national and EU levels. To guarantee a CAP's efficacy, efficiency, and equity, it should be reviewed, assessed, and revised on a regular basis. There is no guidance for how aquaculture actors should adjust, how to evaluate any adaptation, or how to track progress in the absence of explicit sustainability, environmental criteria, or end goals. Therefore, it is still dangerous for aquaculture players when rules lack direction (Aarset et al., 2020).

Regulatory Measures

Regulation relating to production, environmental performance, aquatic animal health and welfare, product quality control, or health and safety might originate from many authorities, ministries, agencies, etc. Aquaculture activities are frequently governed by rules with a broader reach, such as agricultural, environmental, fisheries, food, industrial, and consumer regulations, where there is a lack of specialized national legislation on the subject. Therefore, the governance of aquaculture in Member States is the responsibility of multiple authorities and bodies, each of which has varying timeframes for operational procedures, decision-making, and occasionally overlapping duties (Boyd, 2020).

European Union

The Common Fisheries Policy and the Aquaculture Regulation are two of the laws that have been created in the European Union (EU) to control the mariculture sector. In order to address environmental problems and preserve the industry's long-term sustainability while protecting the environment, regulatory frameworks and standards have been created. Sustainable farming, food safety and quality, animal health, integrated coastal zone management, etc. are all goals of these legislation. On the basis of new scientific discoveries, developments in technology, and shifting market conditions, the EU periodically examines and revises its legislation. For mariculture activities to be profitable, regulations must be followed. Aspects of the EU's mariculture production laws that need improvement are identified. These include streamlining regulatory processes, harmonising state regulations, and increasing regulatory transparency (Bujas et al., 2023).

United States

The federal Clean Water Act established the National Pollutant Discharge Elimination System (NPDES) program to control point source pollution discharges into US waters in order to preserve and enhance water quality. Marine aquaculture is subject to a wide range of environmental rules and regulations in the United States. These rules cover issues related to siting, water quality, waste disposal, aquatic health management, and the impact on marine mammals, endangered species, and vital fish habitat. Government organizations have implemented a number of initiatives in recent years to enhance agency collaboration and regulatory effectiveness without sacrificing environmental protections (Executive Office of the President, 2020). Programmatic approaches to permitting (such as the Army Corps of Engineers Nationwide permits), geographic information system analysis to find the best aquaculture sites with the fewest conflicting uses, consultation with impacted marine space users, government agency collaboration, standardization of aquatic animal health management, improvements in drug approval procedures, and continuous scientific research to better identify and mitigate environmental risks are a few examples (Rubino, 2023).

Canada

In Canada, governments and territories are largely responsible for the monitoring, regulation, and enforcement of freshwater fish. Fish management in some areas and/or governments are also relies on practices like stocking. In contrast to fish management, habitat management in Canadian freshwaters is mainly the task of the federal government: Environment and Climate Change Canada is in charge of harmful substances and water quality (such as contaminants and nutrient pollution), and DFO oversees all other aquatic activities (such as culvert installation and dam construction) that have an impact on freshwater fish habitat in compliance with the Fisheries Act Although some provinces and territories (such as British Columbia, Ontario, and Yukon) have the authority to alter laws through variation orders, freshwater fisheries are governed by federal law (Albert et al., 2021).

China

In the 1970s, the Chinese Academy of Fishery Sciences' Freshwater Fisheries Research Centre (FFRC) was founded in Wuxi, Jiangsu Province, as a fish farming training facility on a commission from the Food and Agriculture Organisation of the United Nations (FAO). By training hundreds of participants from more than 20 nations and regions, this centre has significantly improved freshwater fisheries and biological research on freshwater fish species worldwide and disseminated Chinese aquaculture practices. According to Article 329 Civil Code of the People’s Republic of China, rights to mineral exploration, mining, water intake, and the use of water areas or intertidal zones for fisheries or aquaculture that are legally obtained will all be protected by the law. In order to guide and regulate the formulation of pertinent local pollutant discharge standards in a more scientific, precise, and standardized manner, the Ministry of Ecology and Environment issued Technical Guidelines for the Formulation of Local Standards on Controlling the Discharge of Waste Water from Aquaculture (HJ 1217-2023, hereinafter referred to as Technical Guidelines) in February 2023 (Xu et al., 2023).

Pakistan

Water quality is monitored nationwide by the Pakistan Council of Research in Water Resources (PCRWR). Pakistan's federal and provincial governments will both pass legislation pertaining to the preservation of natural resources. A comprehensive law to prevent pollution of freshwater sources did not exist prior to 1997. The Pakistan Environmental Protection Act of 1997 addresses the problem of water contamination, according to the International Union for Conservation of Nature. According to Section 11 of the PEPA (1997), no one is allowed to release any waste or pollutants that surpass the national environmental quality criteria or discharge effluents. The discharge of domestic or industrial effluents above the provincial environmental quality standard is prohibited at the provincial level by the Punjab Environment Protection (Amendment) Act, 2012, the Balochistan Environmental Protection Act, 2012, the KPK Environmental Protection Act, 2014, and the Sindh Environmental Protection Act, 2014. Pollution control is the responsibility of the environmental protection agency in each province (Rasheed et al., 2021).

Certification schemes

Since 1994, aquaculture production's socioenvironmental and ethical sustainability issues have been addressed through certification as a governance mechanism. Nongovernmental actors and private organizations have developed certification schemes to control the aquaculture sector more sustainably in light of the state-centric policies' limited success and shortcomings in managing resources and addressing issues. Over the past decade, aquaculture certification studies have focused on a number of topics, including sustainability and governance producers' viability and market access, credibility and legitimacy, regulatory constraints and the interaction between national regulations and aquaculture standards, value chains, socioenvironmental performance, community, and institutional suitability (Amundsen, 2022).

Aquaculture Stewardship Council

A well-known voluntary organization called the Aquaculture Stewardship Council (ASC) has created aquaculture certifications for the species that are most in demand in international markets. It was created in collaboration with the World Wildlife Fund (WWF) and the Sustainable Trade Initiative (IDH) through a multi-stakeholder process that was first called the aquaculture dialogues. The ASC claims that their Salmon Standard was developed to provide a high-quality, commercially feasible product with the least possible negative effects on the environment and society. The Aquaculture Stewardship Council prawn standard is one of their many certification requirements for common aquaculture products.The idea behind certification schemes is that by establishing rigorous certification criteria, better market actors will be rewarded with lower costs and preferential treatment from consumers (Bohnes et al., 2019).

Best Aquaculture Practices

The Global Aquaculture Alliance (GAA) is a global, nonprofit organisation that represents people, organisations, and companies involved in seafood and aquaculture worldwide. "To promote responsible aquaculture practices through education, advocacy, and demonstration" is the stated goal of GAA. When environmental awareness efforts threatened the prawn industry, GAA first created certification requirements. GAA's "Best Aquaculture Practices" (BAP) third-party aquaculture certification program was established in 2002 with the goal of enhancing the aquaculture supply chain's economic, social, and environmental performance. The full supply chain of farmed finfish, crustacean, and mollusc species worldwide is covered by BAP certification, including farms, processing facilities, hatcheries, and feed mills. In recent years, GAA has worked to help auditors evaluate adherence to the labour and social requirements in BAP, support aquaculture practitioners in incorporating socially responsible practices into their operations, and launch a new data system. GAA views now as a good opportunity to start a learning exercise that will evaluate the effects and compliance of the BAP certification's social and labour standards and provide insights into how social change occurs in aquaculture (Petrokofsky and Jennings, 2018).

Global G.A.P Aquaculture Standards

Originally known as EurepGAP, GlobalG.A.P. was started in 1997 by retailers who were part of the Euro-Retailer Produce Working Group. British retailers collaborated with continental European supermarkets to meet what they claimed were consumer demands for environmental impact, worker and animal welfare, and product safety. In 2007, EurepGAP was renamed GlobalG.A.P. With over 134,000 farms certified in at least 116 countries, GlobalG.A.P. is currently the most powerful private standard-setting organisation in the world. Global G.A.P. places a strong emphasis on resource efficiency, which helps lessen aquaculture operations' environmental impact. This includes the utilization of feed and water. With 24 of the 28 subdomains in the Wheel of Sustainability covered, GLOBALG.A.P. has the most comprehensive standard, according to the mapping of the certification schemes. ASC (21 of 28) and GAA (20 of 28) are next in line. The Best Aquaculture Practices (GAA-BAP) standards of the Aquaculture Stewardship Council (ASC) and the Global Aquaculture Alliance seem to be more appropriate for promoting sociocultural sustainability than Naturland and Global Good Agricultural Practices (Global GAP) (Osmundsen et al., 2020).

Challenges in Policy, Regulation and certification

Conflicts between economic growth and environmental sustainability

Policy disregards or does not give fair consideration to the stakes of other agents which are affected by the development of aquaculture systems and a lack of participation and consideration of a wider range of stakeholders in the decision-making and policy-formulating processes surrounding implementation of aquaculture" are the reasons behind the people-policy gap (Krause et al., 2015). Global analysis of 165 national public health nutrition policies (PHN) and 158 national fisheries policies had very little coherence between the two sectors. They found that 59% of PHN policies had no or low inclusion of aquatic keywords, and 51% of fisheries policies had no or low inclusion of food security and nutrition keywords. However, for China to fully transition to sustainable feed, further legislative incentives for innovation in the aquafeed industry are required. Chinese policymakers face the primary challenge of determining efficient and effective rules and regulations that direct farmers and other supply chain participants, particularly small- and medium-sized producers to improve environmental outcomes without compromising their financial sustainability. Because of a lack of social permission, an ineffective and disorganized permitting system, and a lack of government initiatives that might help marine aquaculture, the United States produces very little compared to its potential (Rubino, 2023).

Global trade pressures and market access considerations

Coherence may not always be desired because of conflicting or divergent interests; in these situations, it is necessary to be able to recognize the gaps, unrecognized trade-offs, and inconsistencies to manage them and lessen unfavourable effects. To facilitate the integration of policies from many sub-domains, such as integrated and ecosystem-based fisheries methods, it is imperative to identify and steer clear of needless coherence issues. Planning and licensing procedures' complexity and expense have also been identified as obstacles for small-scale farmers and newcomers. Regulatory obstacles may have discouraged Scottish scallop fishermen from pursuing aquaculture. For Brazilian aquaculture managers, the biggest obstacle to aquaculture environmental certifications is the exorbitant expense. This is consistent with comparable findings in other nations, where certificates are criticized for being costly and discouraging small aquaculture producers who depend on fish exports in developing nations (Jeffery et al., 2021). A certification program called the Aquaculture Stewardship Council (ASC) seeks to advance ethical aquaculture. ASC as a move to change the industry, but social issues like fair contracts for farmers, respectable labour rights in the sector, and efficient and open stakeholder consultation involving farmers, workers, communities, and civil society need to be addressed immediately. At the moment, farmers bear the brunt of change rather than the chain as a whole, smallholder farmers are essentially shut out of certification, and social impact studies are of poor quality and efficacy (Kuruk and Peters, 2018).

Conclusion

In conclusion, Policies, regulations and certification schemes are main forces that bring advantages for sustainable aquaculture development. Effective implementation of policies promotes aquaculture production and strengthen governmental infrastructure with reliable and accessible regulatory framework while certification initiatives contributed to responsible market incentives, build consumer trust and compliance with global aquaculture supply chain's social, economic, and environmental performance. Moreover, proper legislation and administration depend on environmental protection, sustainable governess and regulatory standards for aquatic species, food safety and coastal fisheries management. Challenges such as limited monitoring resources, overlapping jurisdictions and the proliferation of certification labels highlight the need for coordination and adaptive approaches. Non-governmental actors and private organizations have developed laws and regulations to control the aquaculture sector more sustainably in light of the state-centric policies' limited success and shortcomings in managing resources and addressing issue. Step forward for integration among international trade rules, national policies and certification is crucial to achieve equitable aquaculture system. Overall, a well-structured framework of regulation and certification necessitates for the maintenance of balance at national and international level to safeguard ecosystem from unacceptable inconsistencies, unrecognized trade-offs, and gaps.

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CHAPTER IX

SOCIOECONOMIC ASPECTS AND COMMUNITY-BASED AQUACULTURE

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Introduction

Community-based aquaculture (CBA) has become a significant model for advancing aquaculture and fisheries development, especially in regions where rural livelihoods remain closely linked to natural resources. Unlike industrial aquaculture systems that rely heavily on private investment and export-oriented production, CBA promotes participatory management, local resource stewardship, and the enhancement of community well-being (De Silva, 2012). The approach builds on social organization and integrates aquaculture into local livelihood systems, food networks, and cultural traditions. Production techniques differ by context ranging from pond farming and rice fish integration to cage culture and seaweed cultivation but the defining feature of CBA lies in its alignment with the social and economic fabric of rural communities (Belton & Little, 2011).

Understanding the socioeconomic dimensions of CBA is essential to evaluating its overall impact. Aquaculture contributes not only to household nutrition but also to income, employment, and resilience against seasonal or economic shocks. In South and Southeast Asia, for instance, aquaculture may account for 20–50 percent of household earnings depending on the system and market access (Ahmed & Lorica, 2002). By providing alternative income during agricultural off-seasons, it enhances household stability and reduces vulnerability (Karim et al., 2011). Nevertheless, the distribution of benefits is often uneven; those with better access to training, inputs, and credit tend to gain the most, raising equity concerns (Jahan et al., 2010). CBA's value extends beyond economic returns. Farmed fish supply essential nutrients protein, fatty acids, and micronutrients that are vital for addressing malnutrition in developing regions (Tacon & Metian, 2013). Studies from Bangladesh and Cambodia show that integrating small indigenous fish species into local aquaculture systems improves the intake of vitamins and minerals, particularly for women and children (Thilsted et al., 2016). When aquaculture initiatives combine production with nutrition education, they more effectively translate yields into improved health outcomes (Kawarazuka & Béné, 2010). This illustrates how CBA links financial, nutritional, and social benefits.

Gender dynamics form another critical component of CBA. Women frequently contribute to hatchery work, feeding, processing, and marketing but often remain under-recognized (Weeratunge et al., 2010). Gender-inclusive initiatives that involve women in leadership and decision-making have demonstrated positive outcomes such as increased income control and household bargaining power (Morgan et al., 2017). Without deliberate inclusion, however, aquaculture projects risk reinforcing existing inequalities, as more lucrative roles may shift to men while women face heavier workloads (Kruijssen et al., 2018). Market access and governance also determine the success of community aquaculture. Reliable input supplies, efficient transport systems, and well-functioning markets are essential for profitability

(Belton et al., 2012). Collective organizations such as cooperatives and producer associations help smallholders pool resources, negotiate better prices, and reduce transaction costs (FAO, 2018). Effective local governance ensures equitable participation and conflict resolution, whereas weak institutions and poor market integration can lead to unequal outcomes (Mills et al., 2011).

Aquaculture's exposure to environmental and market risks further influences its sustainability. Shocks such as floods, droughts, diseases, or price fluctuations can severely affect smallholders. While diversification into aquaculture may enhance resilience, overdependence on external inputs can increase vulnerability (Edwards, 2015). Consequently, contemporary evaluations of CBA increasingly emphasize a holistic framework encompassing economic, social, and environmental dimensions (Klinger & Naylor, 2012). Evidence from development initiatives including those by the International Fund for Agricultural Development (IFAD) and World Fish shows that CBA succeeds when production efforts are integrated with socioeconomic support. Projects that emphasize participatory planning, microfinance access, gender-responsive training, and local market strengthening tend to achieve broader development impacts (Dey et al., 2013). In Bangladesh and Cambodia, for example, community-managed fish culture has increased both output and household equity (Dey & Prein, 2005). Conversely, programs focusing solely on technical aspects without institutional or equity considerations often fail to generate long-term benefits (Belton & Little, 2011).

From a policy standpoint, mainstreaming socioeconomic factors into aquaculture development is critical. Priority actions include incorporating gender and nutrition objectives, empowering community organizations, improving infrastructure and markets, expanding financial and insurance mechanisms, and monitoring social indicators alongside production metrics (FAO, 2018; Morgan et al., 2017). These measures ensure that aquaculture growth contributes to inclusive and sustainable livelihoods. In summary, community-based aquaculture offers a pathway to strengthen rural economies, enhance food security, and promote equitable development. Its success depends on embedding social and economic priorities such as income generation, nutrition, gender equality, and participatory governance into project design and policy frameworks. With continued institutional support and inclusive management, CBA can provide resilient, equitable, and sustainable benefits for rural communities.

1. Historical and Global Context

Aquaculture is far from a modern innovation it has a long and diverse history across civilizations and ecological settings. Archaeological and historical evidence indicates that fish farming has been practiced for thousands of years. In ancient China, written records from the Zhou dynasty (circa 1000 BCE) describe the cultivation of common carp (*Cyprinus carpio*), while Egyptian tomb art from around 2500 BCE depicts the rearing of tilapia (*Oreochromis niloticus*) (Nash, 2011). In the Pacific Islands, Indigenous Hawaiian communities developed sophisticated *loko iʻa* (fishpond) systems that combined engineering, ecology, and community management to ensure sustainable food supply and social cohesion (Costa-Pierce, 1987). These examples reveal that early aquaculture practices were rooted in collective stewardship and cultural values rather than profit-driven motives.

During medieval Europe, aquaculture expanded through monastic institutions, where carp ponds provided reliable food sources during fasting periods (Balon, 1995). These community-managed ponds became integral to both religious and local economies. Meanwhile, in Asia, rice–fish systems continued to evolve, particularly in China and Southeast Asia. Fish contributed to pest control and nutrient cycling, while rice paddies offered suitable environments for fish growth. This symbiotic relationship demonstrated the early integration of aquaculture into local farming systems, embodying many of the principles now central to community-based aquaculture (Halwart & Gupta, 2004). The twentieth century marked a major turning point for aquaculture. Rapid population growth, declining wild fish stocks, and rising demand for protein prompted governments and development agencies to promote aquaculture as a tool for food security and poverty reduction, particularly in Asia and Africa (FAO, 2018). However, these early initiatives were largely technology-focused emphasizing pond construction, monoculture, and hatchery development (Edwards, 2000). While they boosted production, they often neglected social organization, equity, and environmental balance, leading to uneven outcomes across communities.

In response to such limitations, the idea of community-based aquaculture (CBA) gained traction in the late twentieth century, aligning with a broader movement toward participatory and people-centered development (Agrawal & Gibson, 1999). Pioneering initiatives in Bangladesh and Vietnam showcased how groups of farmers could collectively manage fish culture in seasonal floodplains, sharing responsibilities for stocking, maintenance, and harvest (Dey & Prein, 2005). These experiences demonstrated that aquaculture could thrive when built on cooperation, local knowledge, and shared benefit rather than purely technical interventions. Today, aquaculture is the fastest-growing food production sector globally, surpassing capture fisheries in total output by 2020 (FAO, 2020). Within this expansion, community-based approaches remain vital for promoting equitable growth. Across South Asia, for example, NGOs and development agencies have helped form cooperatives and women's groups to manage ponds and cages collectively (Belton & Little, 2011). In Africa, CBA initiatives have been implemented in reservoirs and floodplains, though outcomes vary based on land tenure, resource access, and support services (Brummett & Williams, 2000). In Latin America, indigenous and coastal communities have adopted collective seaweed and shellfish farming systems that link livelihoods with rights-based coastal governance (Valderrama et al., 2015).

Despite its successes, CBA has encountered recurring challenges. Weak governance, unequal benefit sharing, and limited access to markets and infrastructure have constrained outcomes in some projects (Allison, 2011). In certain cases, the introduction of unsuitable species or farming technologies disrupted local ecosystems and reduced community participation (Beveridge et al., 1997). Nevertheless, lessons from global experiences highlight a consistent pattern: sustainable CBA flourishes when ecological conditions, social institutions, and economic opportunities are well aligned. In recent years, CBA has gained recognition as part of the broader global sustainability framework. It directly supports multiple Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 14 (Life Below Water) (FAO, 2020). Climate adaptation strategies have also embraced aquaculture as a means of livelihood diversification for vulnerable floodplain and coastal populations (Troell et al., 2014a). By integrating traditional ecological knowledge with modern innovations such as improved seed, sustainable feed, and value-chain linkages CBA represents both a continuation of ancient community practices and a forward-looking response to modern sustainability challenges.

At the same time, the globalization of aquaculture has brought complex social and environmental issues. For instance, industrial shrimp farming in Asia and Latin America has generated export revenue but often displaced small-scale producers and degraded mangrove ecosystems (Stonich & Bailey, 2000). Against this backdrop, CBA provides a contrasting model centered on empowerment, food sovereignty, and ecological stewardship. Evidence from Asia, Africa, and Oceania continues to affirm that aquaculture achieves the best results when locally managed and socially embedded. Overall, the evolution of CBA reflects both continuity and transformation. From the ancient carp ponds of China to modern seaweed cooperatives in East Africa, it illustrates how collective aquaculture practices adapt to shifting environmental, economic, and cultural contexts. Historically rooted in community cooperation and ecological awareness, CBA today stands as a dynamic approach to achieving sustainable development. Its trajectory from traditional practices to a modern development paradigm demonstrates how local participation and environmental responsibility can coexist with global food security objectives.

1.1 Socioeconomic Importance of Community-Based Aquaculture (CBA)

Community-based aquaculture (CBA) is increasingly recognized as a transformative approach to rural development, particularly in areas where livelihoods depend heavily on natural resources. Its significance extends beyond fish production it supports income diversification, poverty reduction, gender inclusion, improved nutrition, and stronger social networks. Built on principles of collective participation and equitable sharing of benefits, CBA offers an effective way to align aquaculture with broader development objectives, ensuring that growth remains both inclusive and sustainable (Dey et al., 2013).

Livelihoods and Employment

One of the most immediate socioeconomic benefits of CBA is its ability to broaden livelihood opportunities and generate additional income for rural households. In many developing regions, communities rely predominantly on agriculture or capture fisheries, both of which are highly seasonal and vulnerable to climate variability. Incorporating aquaculture at the community level allows families to access an alternative and more stable income stream, thereby reducing economic vulnerability. Evidence from Bangladesh and Vietnam demonstrates that collective fish culture in floodplain areas significantly increases household earnings and strengthens resilience to seasonal or economic shocks (Dey & Prein, 2005). Similar initiatives in African countries have shown that community run pond systems not only provide employment but also stimulate small-scale enterprises and reinforce local economic vitality (Brummett & Williams, 2000).

Poverty Alleviation

CBA plays an instrumental role in reducing poverty and enhancing resilience among resource-dependent communities. By creating new income streams, improving food access, and facilitating entry into local markets, it addresses multiple dimensions of rural poverty simultaneously. Unlike farming or capture fisheries, which often produce only during specific seasons, aquaculture allows for year-round or staggered production, helping stabilize consumption and income (Ahmed & Lorica, 2002). In contexts affected by climate change, CBA also serves as an adaptive livelihood strategy. For example, floodplain aquaculture projects in Bangladesh have enabled households to maintain income and food security during monsoon periods when crops are submerged. In Cambodia, integrated rice–fish systems have improved household nutrition and reduced vulnerability to crop failure. Similarly, community-managed pond systems in Malawi and Nigeria have provided drought-resilient income sources, offering protection against the declining productivity of capture fisheries (Troell et al., 2014a). Beyond immediate economic benefits, CBA contributes to long-term community development. Income generated through collective aquaculture is often reinvested in public goods such as education, healthcare, or local infrastructure thereby strengthening community welfare. Studies by WorldFish (2019) have shown that these reinvestments help build social capital and foster inclusive growth. By combining short-term financial relief with long-term development outcomes, CBA operates as both a poverty reduction and resilience-building mechanism.

Food and Nutrition Security

CBA contributes significantly to food and nutrition security, particularly in rural areas where malnutrition remains prevalent. Fish produced through community systems provide affordable, locally available sources of protein, essential fatty acids, and micronutrients such as vitamin A, iron, and calcium (Thilsted et al., 2016). Small indigenous species, often raised in community ponds or rice fish systems, are especially valuable in addressing micronutrient deficiencies among vulnerable populations. Unlike export-oriented commercial aquaculture, community-based systems frequently reserve part of the harvest for home consumption, ensuring that nutritional benefits reach producers themselves. Projects in Bangladesh and Cambodia that combine aquaculture training with nutrition education have led to measurable improvements in maternal and child health (Kawarazuka & Béné, 2010). Similar initiatives in Malawi show that integrating aquaculture with nutrition awareness campaigns increases household fish consumption and reduces malnutrition rates. CBA systems also promote dietary diversity by incorporating other aquatic organisms such as mollusks, crustaceans, and seaweed (Beveridge et al., 2013). This diversification not only enriches diets but also enhances community resilience by reducing dependence on external food sources. Consequently, CBA strengthens the link between food production, nutrition, and public health at the household and community levels.

Gender and Social Equity

A crucial aspect of CBA lies in its potential to promote gender equity and social inclusion. Women play vital roles throughout the aquaculture value chain from pond preparation and feeding to post-harvest processing and marketing. However, in large-scale aquaculture industries, their labor is often undervalued and their access to training, credit, and leadership roles remains limited (Weeratunge et al., 2010). The community-oriented nature of CBA creates more opportunities for women's participation, as it aligns better with household responsibilities and local resource management structures. When women are involved in decision-making through cooperatives or producer groups, they gain greater control over household income and resource allocation, improving overall family welfare (Morgan et al., 2017). Empirical evidence from Asia and Africa shows that women-led aquaculture groups have increased not only income but also social status and access to services such as healthcare and education. CBA also benefits other marginalized groups such as landless farmers and rural youth by creating shared production spaces like communal ponds or cages. These arrangements ensure that even resource-poor households can engage in aquaculture, reducing inequality and fostering inclusive growth (Kruijssen et al., 2018). When implemented with an equity lens, CBA becomes both a livelihood intervention and a vehicle for social empowerment strengthening women's voices, promoting youth participation, and broadening community inclusiveness.

1.2 Community Institutions and Social Cohesion

Another vital contribution of CBA is its ability to reinforce local institutions and enhance social cohesion. The collective nature of aquaculture requiring shared labor for pond management, stocking, and harvesting encourages cooperation, trust, and participatory governance (Agrawal & Gibson, 1999). These collaborative structures often extend beyond aquaculture, fostering initiatives in natural resource management, microfinance, and collective marketing. In areas where competition over land and water resources is common, organized CBA groups provide a framework for negotiation and conflict resolution, thereby reducing disputes (Mills et al., 2011). For instance, community-managed fishponds in Cambodia have helped establish equitable water-sharing systems among farmers, while aquaculture cooperatives in Sub-Saharan Africa have strengthened local solidarity and market participation. Through these processes, CBA builds social capital and enhances communities' capacity to manage resources sustainably and address shared challenges. As a result, it functions not just as a production strategy but as a catalyst for stronger, more resilient community institutions.

1.3 Local Market Development and Value Chains

CBA also stimulates local markets and enhances participation in aquaculture value chains. The establishment of community aquaculture enterprises generates demand for inputs such as seed, feed, and equipment, creating opportunities for local entrepreneurship (Belton et al., 2012). On the output side, fish harvesting, processing, and marketing activities generate employment for traders and retailers many of whom are women. Collective organizations such as cooperatives improve producers' bargaining power, enabling them to negotiate better prices and reduce dependence on intermediaries. Cooperative marketing initiatives in South Asia, for example, have increased producer profits and ensured that more value remains within communities. By linking production with processing and retailing, CBA contributes to local economic diversification and strengthens rural market systems. These value-chain linkages ensure that the financial and social benefits of aquaculture are more evenly distributed, promoting inclusive rural development.

Table 1. Socioeconomic benefits of community-based aquaculture (Belton, & Little, 2011).

Aspect	Aspect Key Benefits
Livelihoods	Employment generation, income diversification
Poverty alleviation	Reduced vulnerability, reinvestment in community
Food security	Affordable protein and nutrient supply
Gender equity	Empowerment, decision-making, inclusivity
Income	Sources

2. Community Participation and Governance

The effectiveness and long-term sustainability of community-based aquaculture (CBA) are closely linked to how well communities organize themselves and manage governance structures. Strong community participation not only fosters a sense of ownership but also ensures that the benefits of aquaculture are distributed fairly among members. Collective action enhances efficiency, accountability, and resilience, reducing the risks of elite capture or exclusion of marginalized groups (WorldFish, 2019). When communities work together to share responsibilities such as pond management, stocking, feeding, harvesting, and marketing they build cooperation and trust. This participatory approach enables more efficient resource use and supports transparent decision-making processes. It also creates opportunities for mutual learning, where farmers collectively address production challenges and share local knowledge. Such engagement transforms aquaculture from an externally driven intervention into a locally owned enterprise that reflects community priorities and values.

Participatory governance forms the cornerstone of successful CBA initiatives. When local stakeholder’s men, women, and youth are actively involved in planning, implementation, and monitoring, it strengthens transparency and accountability. Inclusive governance also increases the likelihood that aquaculture systems will align with local ecological conditions and cultural norms. Communities that integrate traditional knowledge with scientific input tend to adopt more sustainable and adaptive management practices, ensuring long-term viability of their aquaculture systems. Local knowledge systems play a particularly important role in resource management. Many communities have generations of experience managing aquatic ecosystems, including understanding seasonal variations, water management, and species behavior. Recognizing and incorporating these insights into modern aquaculture programs leads to better ecological outcomes and enhances community commitment to collective rules. External factors including NGOs, research organizations, and government agencies also play a supportive role in community governance. They often provide technical expertise, financial resources, training, and policy guidance (FAO, 2020). Partnerships with these institutions can help build local capacity, facilitate access to credit, and connect small-scale producers to wider markets. However, it is essential that such support empowers communities rather than creating dependency. The most successful programs are those where external partners act as facilitators strengthening community leadership, governance, and long-term self-reliance.

Effective governance structures are often characterized by clear rules, equitable participation, and transparent benefit-sharing. Committees or cooperatives may be formed to oversee production planning, input procurement, and financial management. These bodies help to prevent conflict, promote accountability, and ensure that all members have a voice in decision-making. Moreover, transparent governance improves social cohesion by reinforcing fairness and mutual respect among members. Ultimately, participatory governance is not just an administrative mechanism it is the foundation for social inclusion and sustainability in aquaculture. When communities are empowered to govern their own resources, they are better able to manage risks, adapt to changing environmental or market conditions, and sustain their livelihoods over time. CBA therefore exemplifies a model of development where empowerment, accountability, and shared responsibility combine to promote both productivity and equity.

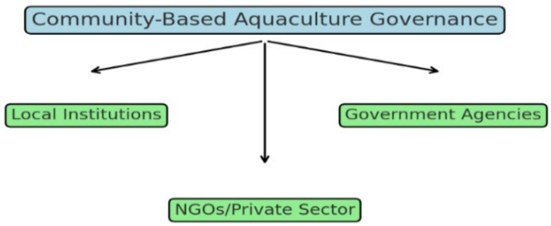

Figure 1. Governance Model of CBA (Agrawal, & Gibson, 1999).

Economic Viability and Market Linkages

The sustainability and long-term success of community-based aquaculture (CBA) depend heavily on its economic viability. While social and nutritional outcomes are important, communities are most likely to sustain aquaculture activities when they generate reliable and meaningful financial returns. Profitability, therefore, becomes a key determinant of whether aquaculture is viewed as a viable livelihood strategy. Economic performance in CBA systems is shaped by several interconnected factors, including input costs, production efficiency, access to credit, and the strength of market linkages that enable producers to sell their harvests at fair prices (Ahmed & Lorica, 2002). In many rural contexts, alternative income opportunities are limited, and households are exposed to financial instability. For this reason, aquaculture must not only recover costs but also produce surplus income that supports family welfare and encourages reinvestment in future production cycles. Communities are more likely to continue aquaculture practices when the financial gains are consistent and clearly visible.

5.1 Cost Benefit Considerations

The long-term financial sustainability of CBA depends on achieving a balance between production costs and income. Community aquaculture often requires shared investments in infrastructure, seed, feed, and water management. In areas where quality inputs are expensive or difficult to obtain, production costs can be high. However, collective management helps mitigate these challenges by spreading risk and pooling resources among multiple households. Studies in South Asia and Africa show that shared investments and collective purchasing reduce per capita expenses, improve access to quality inputs, and increase overall profitability (Dey & Prein, 2005). Microfinance institutions, savings groups, and government subsidies can further strengthen community capacity to invest in aquaculture. Access to affordable credit allows small-scale producers to buy inputs, upgrade facilities, and manage risks more effectively. Group-based financial models, in particular, tend to enhance repayment performance and reduce individual exposure to financial shocks (Kassam & Subasinghe, 2011). Profitability also depends on the type of species cultured, production systems used, and local environmental conditions. Some species offer higher market returns but demand more capital or technical knowledge, while others provide steady, lower-risk income. Consequently, economic planning for CBA should consider both biological and market suitability (World Bank, 2013).

3. Value Chain Development and Market Integration

A robust and inclusive value chain is essential for the economic success of CBA. Value chains extend beyond production, encompassing input supply, processing, transport, and marketing. When communities are able to connect these stages effectively, they capture a larger share of the final value. Establishing small-scale processing facilities such as smoking, drying, or packaging units enables communities to add value and reach new markets (Mills et al., 2011). Direct marketing channels, including cooperatives, farmers' markets, and digital platforms, have also proven valuable in reducing dependence on intermediaries and increasing producer margins (FAO, 2020). In regions where infrastructure allows, digital technologies and mobile platforms are increasingly being used to connect producers with buyers, improving price transparency and expanding market reach. Integration with broader agro-food systems can further enhance resilience. Linking aquaculture with other agricultural enterprises such as rice, vegetables, or livestock creates diversified income sources and reduces vulnerability to single-market fluctuations. This approach not only spreads financial risk but also improves resource efficiency and nutrient recycling across farming systems.

3.1 Infrastructure and Institutional Support

Access to infrastructure and supportive institutions is critical for market integration. Reliable transport networks, cold storage, and processing facilities reduce post-harvest losses and enable producers to access larger and more stable markets. Collective organizations such as producer cooperatives and fisheries associations provide vital services, including training, bulk purchasing, and marketing assistance. Public private partnerships have shown particular promise in strengthening CBA value chains. In Vietnam, for example, collaboration between farmer cooperatives, private hatcheries, and export-oriented processors has helped smallholders meet quality standards and enter global seafood markets (Bush et al., 2010). Similar partnerships in Africa and South Asia have expanded domestic market access and improved the profitability of small-scale producers.

3.2 Market Dynamics and Financial Resilience

Global and domestic market trends also influence the viability of community aquaculture. Growing demand for fish, driven by urbanization and income growth, offers new opportunities for small producers (FAO, 2022). Domestic markets for affordable, fresh fish are particularly important for CBA systems, as they provide stable and accessible outlets for production. However, engagement in export markets can be challenging, as meeting international food safety and certification standards requires significant capacity building and investment (Belton et al., 2012). Access to financial and risk management tools further enhances resilience. Microcredit schemes, cooperative savings groups, and insurance programs provide a safety net against production losses due to floods, disease, or price drops (Muir, 2013). Collective arrangements typically enjoy greater bargaining power with financial institutions, improving access to credit and insurance compared to individual farmers. The expansion of CBA also generates multiplier effects in local economies. Increased aquaculture activity stimulates demand for feed, seed, transport, and processing services, creating indirect employment and supporting small enterprises (Dey et al., 2008). This circulation of income within the community enhances rural economic vitality and strengthens local markets. Nevertheless, challenges of equity and inclusivity persist. Without transparent governance and fair benefit-sharing, wealthier households may capture a disproportionate share of profits. To prevent this, CBA programs must prioritize inclusive participation, equitable access to credit, and mechanisms that protect the interests of marginalized groups (Agrawal & Gibson, 1999).

Table 2. Economic challenges and opportunities in CBA (FAO, 2018).

Economic Factor	Challenges	Opportunities
Cost-benefit	High input costs	Shared infrastructure
Finance	Limited access to credit	Microfinance, subsidies
Market integration	Exploitation by intermediaries	Cooperatives, digital platforms

4. Environmental and Social Challenges

Although community-based aquaculture (CBA) has proven effective in improving livelihoods and food security, it also faces several environmental and social challenges that limit its sustainability and scalability. These challenges differ by context but generally relate to ecosystem stress, climate vulnerability, governance weaknesses, market constraints, and social inequities. Unless addressed comprehensively, such factors may hinder the ability of CBA to function as an inclusive and environmentally responsible development model.

Environmental Pressures

Even though CBA typically operates on a smaller scale than industrial aquaculture, it still places significant demands on natural resources such as water, seed, and feed. Poorly planned pond construction can damage wetlands, cause soil erosion, and alter hydrological patterns, thereby reducing biodiversity and ecosystem services (Primavera, 2006). In densely populated regions, nutrient runoff and waste from multiple small aquaculture units can contribute to eutrophication, algal blooms, and oxygen depletion (Beveridge et al., 2013). Disease outbreaks present an additional threat to production sustainability. Pathogens such as white spot syndrome in shrimp or *Streptococcus* infections in tilapia have caused devastating losses globally. Small-scale producers, who often lack access to veterinary services or biosecurity facilities, are particularly vulnerable to these shocks (Subasinghe et al., 2001). Managing disease and maintaining environmental quality therefore require collective planning, water management, and adherence to sustainable farming practices.

5. Climate Change Vulnerabilities

CBA systems are highly sensitive to the impacts of climate change. Floods, droughts, temperature fluctuations, and salinity intrusion can severely affect aquaculture infrastructure and productivity. In coastal and deltaic regions, rising sea levels and storm surges threaten freshwater ponds, while erratic rainfall patterns disrupt seasonal production cycles (De Silva & Soto, 2009). Most community aquaculture projects operate with limited access to climate-resilient technologies, early warning systems, or adaptive infrastructure. Without such tools, communities remain exposed to environmental shocks that can undermine long-term viability. Climate adaptation strategies such as improved pond design, species diversification, and integrated farming systems are therefore essential to strengthen resilience.

Equity and Governance Challenges

While CBA is designed to be participatory, unequal distribution of benefits is common. Wealthier or more influential households sometimes dominate leadership roles, decision-making, and access to resources, a phenomenon known as “elite capture” (Agrawal & Gibson, 1999). This undermines inclusivity and can create internal divisions that weaken collective action. Gender inequality is another persistent issue. Although women contribute substantially to aquaculture through tasks such as feeding, processing, and marketing they often receive limited recognition, training, or financial returns for their labor (Weeratunge et al., 2010). Without deliberate gender-sensitive interventions, aquaculture programs risk reproducing existing social hierarchies rather than challenging them (Kruijssen et al., 2018). To ensure equitable outcomes, governance frameworks must include transparent decision-making, fair benefit-sharing mechanisms, and representation for women and marginalized groups. Participatory governance models that build accountability and empower community voices are essential for long-term social sustainability.

Resource Conflicts

Competition over access to land and water resources frequently creates tension between aquaculture groups and other users. In floodplain areas, conflicts may emerge when aquaculture restricts access to common fishing grounds or agricultural land (Mills et al., 2011). During dry seasons, competing demands for irrigation and aquaculture water can exacerbate disputes among farmers, fishers, and livestock owners. These conflicts highlight the need for clear tenure arrangements and locally grounded conflict-resolution mechanisms. Participatory resource management frameworks where all user groups are involved in planning and decision-making are vital to balance competing interests and maintain community harmony.

Institutional and Market Limitations

Many CBA initiatives are introduced through short-term projects that struggle to remain functional after donor or government support ends. Weak institutional capacity, limited technical skills, and poor financial management often undermine long-term sustainability. In some cases, communities also face regulatory barriers or difficulties adapting to market fluctuations (Bush et al., 2010). Market challenges further compound these issues. Small-scale producers frequently depend on intermediaries who capture a large share of profits. Poor transport networks and lack of cold storage lead to post-harvest losses and reduced income. Without adequate business training, communities may also struggle to negotiate fair prices or establish stable market linkages. Strengthening cooperatives, improving infrastructure, and roviding entrepreneurship training are therefore essential for enhancing market resilience.

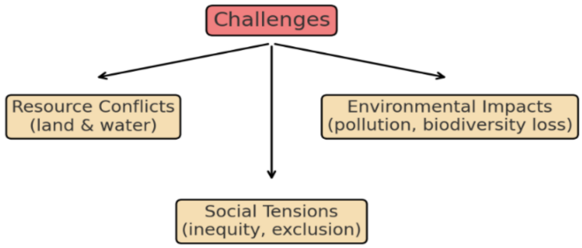

Figure 2. Environmental and Social Challenges in CBA (Troell et al., 2014b).

6. Policy and Institutional Support

Strong policy frameworks, institutional backing, and infrastructure development are essential components for scaling up and sustaining community-based aquaculture (CBA). Government agencies, non-governmental organizations (NGOs), and international development partners each play critical roles in enabling these systems to thrive. Supportive policies can help remove barriers to participation, improve access to credit and inputs, and ensure that community-based initiatives align with national food security and rural development objectives (World Bank, 2013). Public institutions contribute to CBA primarily through extension services, training programs, and infrastructure development. Extension services provide technical guidance, such as pond management practices, species selection, and disease prevention, while training programs build local capacity for governance, financial management, and gender inclusion. Investment in essential infrastructure roads, cold storage, hatcheries, and market facilities reduces post-harvest losses and connects small producers to larger markets. International organizations, including the Food and Agriculture Organization (FAO) and WorldFish, have been instrumental in promoting community-centered aquaculture models. They offer research-based guidance, financial assistance, and pilot projects that demonstrate best practices in inclusive aquaculture (FAO, 2020; WorldFish, 2019). These organizations also support governments in designing policies that protect community rights to aquatic resources and promote environmentally responsible practices. Successful policy environments typically share several characteristics:

- **Recognition of community resource rights**; secure tenure and legal frameworks that allow communities to manage and benefit from local aquatic resources.
- **Participatory planning and governance**; Mechanisms that include farmers, women, and marginalized groups in decision-making processes.
- **Integration with national development goals**; Alignment of aquaculture strategies with broader objectives such as poverty alleviation, food security, and climate adaptation.

- **Supportive financial mechanisms**; Availability of microcredit, insurance, and cooperative savings schemes that enable smallholders to invest and manage risk.
- **Institutional coordination**; Effective collaboration between ministries, NGOs, and private-sector actors to ensure coherent implementation.

By establishing enabling environments that address these dimensions, governments and development partners can help transition CBA from small, project-based initiatives into sustainable, community-driven enterprises. Institutional support must prioritize local empowerment rather than dependency, ensuring that communities have the capacity, rights, and resources to sustain aquaculture independently. Ultimately, policy and institutional support form the backbone of resilient community aquaculture systems. When well-designed, they provide the legal, technical, and economic foundations that allow CBA to contribute meaningfully to national food production, rural employment, and environmental sustainability.

7. Case Studies

Community-based aquaculture (CBA) practices vary across regions, reflecting differences in ecology, governance, and socioeconomic context. The following case studies from Bangladesh, the Philippines, and Sub-Saharan Africa illustrate how CBA has been implemented under diverse conditions, highlighting both achievements and challenges. Bangladesh is widely regarded as a pioneer in community-based aquaculture. Numerous projects often led by organizations such as WorldFish and supported by international development partners have demonstrated the capacity of CBA to enhance rural livelihoods and empower women. Women-led aquaculture cooperatives have become particularly influential. Through shared pond management, collective purchasing of inputs, and group-based marketing, these cooperatives have generated steady income for rural households while increasing women's participation in decision-making processes (Kruijssen et al., 2018). The inclusion of women in aquaculture activities has not only boosted household earnings but also improved social recognition and access to resources. Community-managed fish culture in seasonal floodplains has proven effective in improving food and nutrition security. Groups of farmers collaborate to stock, manage, and harvest fish during flood seasons, distributing the proceeds among members. These systems enhance household dietary diversity and strengthen food supply during lean agricultural periods. However, challenges remain, including limited access to credit, dependency on donor funding, and difficulties sustaining collective management after external support ends.

In the Philippines, CBA has been integrated into coastal resource management initiatives that emphasize ecological restoration and livelihood development. Community-managed coastal aquaculture such as the rearing of milkfish, seaweed, and shellfish has been instrumental in rehabilitating degraded ecosystems while improving income for small-scale fishers (WorldFish, 2019). Coastal communities in regions like Bohol and Mindanao have established collective aquaculture enterprises that combine traditional knowledge with modern practices. These initiatives often operate under co-management frameworks, where local fishers' associations collaborate with local governments to regulate resource use and ensure equitable benefit-sharing. The Philippines' experience demonstrates that integrating CBA with environmental stewardship can produce dual outcomes: ecological recovery and social resilience. Nonetheless, issues such as limited infrastructure, exposure to typhoons, and market fluctuations continue to challenge the long-term sustainability of these community projects. Across Sub-Saharan Africa, CBA has gained attention as a strategy for food security and poverty alleviation. Smallholder fishpond projects, often supported by NGOs and government extension services, have created employment and supplemental income in rural areas (World Bank, 2013). In countries like Malawi, Uganda, and Nigeria, community-managed pond systems have been established to strengthen local economies and provide accessible protein sources. These projects typically emphasize group-based training, shared infrastructure, and participatory governance. Some communities have also adopted integrated aquaculture–agriculture systems, combining fish production with crop and livestock farming to optimize resource use. While CBA in Africa has produced promising results, persistent challenges remain particularly in maintaining access to quality seed and feed, improving cold-chain logistics, and ensuring equitable participation across gender and income groups. Continued institutional support and investment in local market infrastructure are necessary to ensure scalability and long-term success.

8. Future Perspectives

Community-based aquaculture (CBA) continues to evolve in response to technological innovation, sustainability imperatives, and shifting development priorities. The coming years are expected to bring significant changes in how CBA is designed, managed, and scaled. Emerging practices such as climate-smart aquaculture, integrated multi-trophic systems, and digital tools for market access are reshaping the sector's potential to address global food and livelihood challenges (FAO, 2020). These innovations aim to strengthen productivity, environmental responsibility, and inclusivity while aligning aquaculture with the broader goals of sustainable development. Moving forward, the success of CBA will depend on its ability to maintain participatory principles while embracing innovation. Ensuring meaningful involvement of women, youth, and marginalized groups will remain central to maximizing social impact and avoiding elite capture of benefits. Inclusive governance will help ensure equitable decision-making and stronger community ownership. Scaling up CBA will also require enabling environments that include sustainable financing, supportive policies, and integration into national food and development strategies (WorldFish, 2019). Governments and institutions will need to invest in infrastructure, capacity building, and technology transfer while supporting communities to manage their aquaculture systems autonomously. The future of aquaculture, particularly when grounded in community participation, holds considerable promise for achieving social, economic, and environmental objectives simultaneously. CBA’s potential to contribute to multiple Sustainable Development Goals (SDGs) including poverty reduction, food and nutrition security, gender equality, and sustainable resource use positions it as a critical development pathway for the coming decades.

Key Future Directions

1. Climate Adaptation and Resilience

Aquaculture will increasingly serve as an adaptation strategy for communities vulnerable to floods, droughts, and salinity intrusion. Climate-smart approaches such as integrated rice fish systems, polyculture, and low-carbon aquaculture will help reduce vulnerability and strengthen environmental resilience. CBA’s collective nature supports shared risk management, making it particularly suited for climate adaptation.

2. Digital and Technological Innovation

Rapid advancements in digital technology will transform community aquaculture. Mobile applications for weather forecasting, water-quality monitoring, and market price tracking will enhance productivity and transparency. Digital platforms can also connect small producers directly with buyers, reducing dependence on intermediaries and expanding income opportunities. Low-cost technologies such as bio floc systems, solar-powered aeration, and smart feeding tools will further improve efficiency and sustainability.

3. Gender and Youth Empowerment

Empowering women and youth remains essential for inclusive growth. Women already contribute substantially to aquaculture, but expanding their roles in leadership, entrepreneurship, and decision-making can increase household welfare and community development. Similarly, involving young people in digital innovation, marketing, and technical training can make aquaculture more dynamic and future-oriented (Kruijssen et al., 2018).

4. Economic Diversification and Value Chain Development

Strengthening aquaculture value chains will be critical for economic resilience. Communities that invest in local processing, cooperative marketing, and product diversification will capture greater value from production. Certification schemes, fair-trade models, and niche marketing for sustainably farmed products can help connect small producers to regional and global markets. In developing nations, these mechanisms could also boost foreign exchange earnings and expand rural employment opportunities.

5. Policy and Institutional Strengthening

Policy support will continue to play a decisive role in shaping the future of CBA. Governments can promote sustainability by integrating community aquaculture into rural development, food security, and climate policies. Institutional frameworks that provide access to microfinance, insurance, and capacity-building programs will further enable communities to expand operations sustainably. Collaboration between government, NGOs, and private-sector partners will be key to ensuring consistent policy implementation and support.

6. Sustainability and Environmental Stewardship

Environmental responsibility will remain central to future aquaculture systems. Encouraging eco-friendly production models such as aquaponics, mangrove-based aquaculture, and integrated multi-trophic systems will reduce ecological impacts. Certification and eco-labeling can incentivize sustainable practices, linking producers to environmentally conscious consumers. Embedding these approaches within CBA frameworks ensures that economic gains do not come at the expense of environmental integrity.

Conclusion

Community-based aquaculture (CBA) has emerged as a cornerstone of sustainable rural development, offering a practical and inclusive approach to addressing food security, livelihood diversification, and environmental management. Unlike commercial aquaculture, which often prioritizes profit over equity, CBA builds upon community knowledge, shared resources, and collective governance to achieve both social and economic goals. Throughout its evolution, aquaculture has shifted from small-scale subsistence practices to globally integrated food systems. Within this transformation, CBA has provided an alternative model one that aligns productivity with participation and environmental care. For many rural and coastal populations, it offers accessible opportunities for livelihood diversification, employment creation, and income generation while reinforcing community resilience and cooperation. The socioeconomic contributions of CBA are multidimensional. Beyond producing food and income, it strengthens local economies through value-chain participation, enhances nutrition through increased fish consumption, and promotes gender equity by engaging women in decision-making and enterprise management. These collective benefits contribute directly to poverty alleviation and social inclusion in resource-dependent communities. However, realizing the full potential of CBA depends on ensuring its economic and institutional sustainability. Profitability must be coupled with equitable benefit-sharing, access to affordable inputs, and reliable market connections. Strengthening local cooperatives, improving infrastructure, and fostering transparent governance are critical for maintaining long-term viability. Market integration while essential for growth should be managed carefully to prevent exploitation by intermediaries and ensure that community producers retain fair value for their products. Environmental and social challenges remain among the most pressing concerns. Issues such as disease outbreaks, habitat degradation, and the impacts of climate change continue to threaten small-scale aquaculture. Likewise, inequitable participation and resource competition can weaken collective action. Addressing these challenges requires a holistic approach that integrates ecosystem management, social equity, and participatory governance. Looking ahead, strong policy frameworks, institutional partnerships, and inclusive innovation will be vital to sustaining and expanding community-based aquaculture. Governments, NGOs, and research institutions must collaborate to provide infrastructure, technical training, financial services, and regulatory support tailored to community needs. The integration of climate-resilient practices, low-cost technologies, and equitable financing mechanisms will help ensure that CBA remains adaptive and future-ready. Ultimately, CBA represents far more than a production system it is a pathway toward inclusive development, environmental stewardship, and social empowerment. By combining community knowledge with modern innovation and embedding principles of fairness, cooperation, and sustainability, CBA can transform rural economies and contribute meaningfully to global food systems. Achieving this vision requires ongoing commitment to participatory governance, equitable benefit-sharing, and environmental care. If these principles are upheld, community-based aquaculture can evolve from a promising initiative into a resilient engine of sustainable development benefiting both people and the planet.

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CHAPTER X

FUTURE DIRECTIONS AND SOLUTIONS FOR SUSTAINABLE AQUACULTURE

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1 Frameworks and Dimensions of Sustainable Aquaculture

1.1 Environmental, Economic, and Social Pillars of Aquaculture Sustainability

Sustainability in aquaculture is framed by the classic "triple-bottom-line" environmental, economic, and social pillars. They must coexist and mutually reinforce one another. In practice, this means that farming systems must be ecologically sound (e.g., minimizing pollution, preserving habitat) and economically viable and socially responsible. The three-pillar triple-bottom-line environmental, economic, and social framework controls sustainability in fish farming. They should be in harmony with each other and complement each other. Practically, it implies that farming systems should be both environmentally friendly (e.g., less contamination, living well, etc.) and profitable and less socially discriminative. There is explicit outcome measurement along all three dimensions through certification and a performance indicator framework. Recent empirical studies indicate that well-operating aquaculture can realize synergies among these pillars: in 57 cases around the globe, Garlock *et al*. (2024) discovered statistically significant relationships between environmental, economic, and community performance. Economically successful farms, in most cases, also provide social benefits, and with most systems, better treatment of the environment goes hand in hand with better social benefits. Nonetheless, it is not the default option; Osmundsen *et al*. (2020) propose that in many cases, sustainability schemes concentrate overwhelmingly on the ecological indicators and the related governance.

1.2 Balancing Productivity with Ecosystem Health (Climate Resilience)

Sustainable aquaculture should produce enough food to meet the demand, while preserving the ecosystem's health and helping to build resilience against climate change. One of the innovations is integrated multi-trophic aquaculture (IMTA), recirculating systems and better feed to recycle the nutrients and reduce pollution. Climate change adds further challenges. Rising water temperatures, sea-level rise, and increased disease risk can stress farms. Maulu *et al.* (2021) noted most climate impacts are negative (e.g. heat stress, extreme weather), though some (e.g. CO_2 fertilization of algae) could be positive. They emphasize the need for short-term adaptation (e.g. selective breeding for heat tolerance, storm-resistant infrastructure) and long-term mitigation. Aquaculture itself can be relatively climate-friendly: producing 1 kg of farmed fish generally requires less feed and causes lower greenhouse gas emissions than equivalent protein from cattle.

The successful implementation of these strategies is highly dependent on effective government policy (Waite *et al.,* 2014). The potential of aquaculture to enhance global food system resilience will not be realized without policies that provide adequate incentives for resource efficiency, equity, and environmental protection. The FAO's Blue Growth program and its related projects in Asia are examples of how policy can support the transition to more sustainable and climate-resilient farming practices (Guo & Zhou, 2022).

Real-world case studies illustrate both the potential and the pitfalls of this balance. In Egypt, a project focused on improving Nile tilapia farming demonstrated a clear win-win scenario: by providing farmers with a fast-growing fish strain and training them in best management practices, the project not only boosted their income but also reduced the lifecycle environmental impacts of their operations by up to 36% (Bunting, 2024). This example validates the core finding that productivity and environmental protection can be mutually reinforcing. In contrast, a study on Indonesia's aquaculture sector found that achieving ambitious production targets was not possible without devastating environmental costs, particularly concerning land use, freshwater supplies, and the depletion of wild marine resources for feed (Martinell *et al.,* 2024).

2 Advanced environmental technologies and ecological approaches

An increasingly important area of food production that is vital to the world's food security is aquaculture. This presents both possibilities and challenges for striking a balance between sustainability, innovation, and environmental stewardship and financial rewards. Therefore, it is crucial to comprehend how to handle the intricate interactions between these elements (Ohia, 2025). To advance sustainable aquaculture and improve food and nutritional security, aquaculture specialists are creating innovative technology. Recirculating aquaculture systems (RAS), a closed-loop system that recycles water in a controlled environment, are one of the major developments.

By raising many species in the same habitat, integrated multitrophic aquaculture (IMTA) maximizes resource use and lessens environmental impact and operating expenses. Aquaponics (aquaculture + hydroponics) is an integrated system that uses fish waste to nourish plants while the plants help clean the water for recirculation. In addition to these techniques,

2.1 Recirculating aquaculture system (RAS): innovation and application

RAS also mitigate the risk of disease transmission, escapement, and pollution by isolating farmed fish from natural populations and the surrounding environment (Lal *et al.,* 2024).

Advantages

Advantages include reduced land and water needs (e.g., producing 500 MT/year on the same area as traditional methods yielding 2-10 MT/ha), lower effluent discharge and enhanced disease control. However, challenges involve high initial capital costs, energy demands, and the need for skilled monitoring. Environmental impact assessments compare RAS favorably to raceway systems, showing lower ecological footprints in terms of water usage and waste management.

2.1.2 Fish species commonly cultured in RAS

✓ The most commonly cultured fish species in recirculatory aquaculture systems are:

Tilapia Catfish Striped bass Carp

2.1.3 Basic Innovations in RAS

System optimization and effective water treatment are the main areas of basic RAS advances. To avoid biofilter blockage, particles like feces and uneaten feed are removed using mechanical filtering techniques like sedimentation or drum filters.

2.1.4 Advanced Innovations in RAS

Advanced inventions prioritize automation, biotechnology integration, and sustainability. Utilizing electron donors like methanol to lower oxygen and carbon requirements, nitrate denitrification utilizing anaerobic reactors or Anammox processes eliminates nitrates (1–166 mg NO_3-N/L/h). In membrane photobioreactors (MPBRs), microalgae integration can possibly save fertilizer costs by 60% by recycling nitrogen and phosphate from wastewater, producing oxygen through photosynthesis, and sequestering CO_2. By encouraging microalgae-bacteria symbiosis for in-situ water treatment, Biofloc technology (BFT) reduces the need for fishmeal (Liu *et al.,* 2020). Real-time water quality monitoring is made possible by intelligent biosensors, which can identify variables like pH and ammonia (Li *et al.,* 2020).

2.1.5 Applications of RAS

Basic RAS applications are prevalent in hatcheries and juvenile production, supplying fingerlings for grow-out. They support high-value species like tilapia, eel, and sturgeon, as well as niche markets for live or premium fish, leveraging biosecurity and sustainability. For instance, RAS facilities produce millions of smolts annually for species like salmon, ensuring consistent supply. Particle sieve analysis improves solids removal efficiency, enhancing water treatment (Brinker *et al.,* 2020). Economic feasibility studies confirm viability for species like goldfish in small-scale setups (Yanong *et al.,* 2021). Applications also include farming species like trout with minimal water exchange to meet environmental standards and producing marine species like turbot under controlled conditions to shorten growth cycles.

2.2 Integrated Multi-Trophic Aquaculture (IMTA) for Ecosystem Resilience

In order to recycle waste and improve ecosystem resilience, Integrated Multi-Trophic Aquaculture (IMTA), a sustainable aquaculture technique, grows species from several trophic levels close together, simulating natural ecosystems. It combines extractive species like seaweeds, which absorb inorganic nutrients, and shellfish or deposit-feeders, which devour organic materials, with fed species, such as shrimp or finfish.

2.2.1 Basic Concepts of IMTA

Co-culturing organisms from various trophic levels to produce a balanced, self-sustaining system is the fundamental idea behind IMTA. Species that are fed external feed, such finfish (like salmon) or crustaceans (like shrimp), produce both organic (like excrement and uneaten feed) and inorganic (like nitrogen and phosphorus) wastes. While inorganic extractors, such as seaweeds (e.g., kelp, Ulva), absorb dissolved nutrients by photosynthesis, organic extractors, such as mussels, oysters, or sea cucumbers, filter particulate materials (Chopin *et al.,* 2022). This nutrient recapture mimics natural food webs, reducing waste discharge and environmental degradation.

2.2.2 IMTA and Ecosystem Resilience

By encouraging nutrient cycling and lowering human stresses, IMTA improves ecosystem resilience. Excess nutrients in monoculture aquaculture reduce resilience by altering habitat, causing hypoxia, and lowering biodiversity. By internalizing wastes, IMTA lessens this. Seaweeds absorb CO_2 and provide oxygen, and deposit-feeders like sea cucumbers break down benthic organic matter to improve the health of the sediment and avoid sulfide accumulation (Chopin *et al.,* 2022). This multi-layered approach increases adaptive capacity to stressors like ocean acidification or heatwaves, driven by climate change. Indicators such as biodiversity indices, which rise as a result of habitat building by extractive species, and nutrient assimilation efficiency, which improves dissolved oxygen by 35% with sea cucumber integration, are used to quantify resilience (Nissar *et al.,* 2023). Evaluations of circularity reveal that IMTA systems are excellent at managing nutrients and resources, minimizing environmental impact, and fending off pollution events and algae blooms.

2.2.3 Advanced Innovations in IMTA

Modern IMTA systems use optimization and technology to achieve commercial scalability. In order to optimize stocking densities (e.g., >3.9 sea cucumbers/m^2 for maximal organic removal), numerical modeling—such as three-dimensional ocean models—simulates nutrient fluxes and waste mitigation (Chopin *et al.,* 2022). Selective breeding for robust plants and the incorporation of biofloc for microbial nutrient recycling are examples of biotechnology developments (Nissar *et al.,* 2023).

Automation uses sensors to monitor water parameters in real time, allowing for adaptive management. Variable-speed pumps and AI-driven feed systems maximize nutrition distribution while consuming less energy (Knowler *et al.,* 2023). In order to reduce land usage and improve resistance to coastal pressures, offshore IMTA extends to open ocean locations and integrates with renewables such floating solar (Troell *et al.,* 2023). Valorization methods, including hydrothermal liquefaction, close loops in circular models by turning waste into feed or biofuels (Chopin *et al.,* 2022). Additionally, innovations include hybrid land-sea setups with aquaponics for nutrient recycling and zero-water-discharge systems for super-intensive shrimp cultivation (Neori *et al.,* 2024).

2.2.4 Challenges and Future Directions

High startup costs, complicated regulations, and scale problems are some of the difficulties IMTA confronts. Research on species synergy is necessary because operational concerns include disease transmission and inadequate nutrient matching (Granada *et al.,* 2022). Diversification increases economic viability, but co-product markets, such as those for seaweed, require expansion (Alexander *et al.,* 2023). Large-scale experiments, AI-powered predictive modeling, and climate-adaptive systems are the future. By 2025, IMTA may be at the forefront of sustainable aquaculture, promoting ecosystem health and global food security via increased resilience.

2.3 Biofloc Technology for Waste-to-Resource Conversion in Aquaculture

Biofloc Technology (BFT) is a sustainable aquaculture approach that transforms waste into valuable resources by utilizing microbial communities to recycle nutrients and maintain water quality. By manipulating the carbon-to-nitrogen (C:N) ratio, typically between 10:1 and 20:1, BFT promotes the growth of heterotrophic bacteria, which convert nitrogenous wastes—such as ammonia from fish excreta and uneaten feed—into microbial biomass known as bioflocs.

2.3.1 Principles of Biofloc Technology for Waste Conversion

BFT operates by maintaining a high C:N ratio to stimulate heterotrophic bacterial growth, which assimilates nitrogenous waste into biofloc biomass. Organic carbon sources, such as molasses, wheat bran, corn starch, or agricultural byproducts like rice husk, are added to achieve C:N ratios of 10:1 to 20:1, favoring bacterial assimilation over autotrophic nitrification (Nisar *et al.,* 2022). The system requires:

- ✓ Aeration Systems
- ✓ Tanks or Ponds
- ✓ Monitoring Tools

The process begins with microbial inoculation (e.g., Bacillus sp. at 10^6 CFU/mL) or natural colonization over 2-4 weeks. Bioflocs, aggregates of bacteria, algae, protozoa, and organic matter (50-200 µm), effectively recycle waste into a resource consumed in-situ by aquaculture species (Debbarma *et al.,* 2023).

2.3.2 Mechanisms of Waste-to-Resource Conversion

BFT transforms aquaculture waste into valuable resources through several mechanisms, addressing both environmental and economic challenges:

- ✓ Nitrogen Recycling
- ✓ Organic Matter Utilization
- ✓ Probiotic Benefits
- ✓ Biomass Valorization
- ✓ Effluent Reduction

For example, biofloc-based fertilizers enhance soil microbial activity, while biogas supports energy self-sufficiency in aquaculture operations (Lal *et al.,* 2024).

2.3.3 Applications of Waste-to-Resource Conversion in BFT

BFT's waste-to-resource conversion is applied across various aquaculture systems, scales, and species, offering practical and commercial benefits:

- ✓ Feed Supplementation in Grow-Out Systems
- ✓ Hatchery and Nursery Systems
- ✓ Fertilizer Production
- ✓ Bioenergy Generation
- ✓ Integration with Multi-Trophic Systems

These uses highlight BFT's adaptability in lowering environmental effects, promoting economic viability, and turning waste into valuable aquaculture products. Socially, BFT encourages the production of seafood in an environmentally responsible manner, appealing to markets that value sustainability and improving community lives through a variety of outputs (Lal *et al.,* 2024).

2.3.4 Challenges in Waste-to-Resource Conversion

Implementing BFT for waste-to-resource conversion faces several challenges:

- ✓ Operational Complexity
- ✓ Market Development
- ✓ Technical Expertise
- ✓ Regulatory Hurdles

These difficulties show that in order to fully achieve BFT's potential in waste-to-resource conversion, technical training, affordable technology, and market expansion are required (Elvines *et al.,* 2023).

2.3.5 Future Directions for Waste-to-Resource Conversion

Future advancements in BFT focus on enhancing waste-to-resource conversion to improve scalability and sustainability in aquaculture:

- ✓ Optimized Biomass Processing
- ✓ Renewable Energy Integration
- ✓ Microbial Engineering
- ✓ Expanded Species Applications
- ✓ Policy and Market Support

2.4 Aquaponics and Circular Production Model in Sustainable Aquaculture

Fish farming and hydroponic plant growing are combined in aquaponics, a revolutionary aquaculture technique that creates a cyclical production paradigm in which waste from one component is used as a resource for another.

2.4.1 Principles of Aquaponics for Circular Production

Fish, plants, and microbes work together symbiotically in aquaponics to create an environment that can maintain itself. Nitrifying bacteria, such as Nitrosomonas and Nitrobacter, transform fish waste, which is high in ammonia and organic matter, into nitrates, which are the main nutrient for hydroponic plants.

2.4.2 Mechanisms of Circular Production in Aquaponics

The circular production model in aquaponics relies on nutrient recycling and waste valorization, transforming fish waste into productive resources through several mechanisms:

- ✓ Nutrient Recycling Water Conservation
  Multiple Outputs
- ✓ Probiotic Effects Carbon Sequestration

These mechanisms create a closed-loop system where waste is internalized, reducing environmental impacts and generating multiple products, thereby enhancing sustainability and economic returns (FAO, 2022).

2.4.3 Applications of Aquaponics in Circular Production

Aquaponics' circular production model is applied across diverse aquaculture contexts, from small-scale to commercial systems, leveraging waste-to-resource conversion:

- ✓ Small-Scale Rural Systems Commercial Aquaculture Urban Aquaculture
- ✓ Integrated Multi-Trophic Aquaculture (IMTA) Waste Valorization

These applications highlight aquaponics' ability to convert fish waste into food, fertilizers, and energy, supporting sustainable aquaculture and circular economies (Nair *et al.,* 2025).

2.4.4 Advanced Innovations in Aquaponics

Recent advancements (2022-2025) enhance aquaponic circular production model through technological and biological innovations:

- ✓ Microbial Optimization Alternative Inputs Energy Efficiency
- ✓ Automation and Connected Sensor Network (CSN) System Hybrid Systems

These innovations improve scalability, reduce resource inputs, and strengthen the circular model by maximizing waste valorization, making aquaponics a viable solution for large-scale sustainable aquaculture (Channa *et al.,* 2025).

2.4.5 Challenges in Aquaponics Circular Production

Despite its benefits, aquaponics faces several challenges in implementing a circular production model:

- ✓ Technical Expertise Market Development Energy Dependence
- ✓ Regulatory Hurdles System Balance

These challenges highlight the need for cost-effective technologies, technical training, and policy support to scale aquaponics as a circular production model (FAO, 2022).

2.4.6 Future Directions for Aquaponics

Future advancements aim to strengthen aquaponics' circular production model for broader adoption in sustainable aquaculture:

- ✓ Cost-Effective Designs Scalable Modular Systems Digital Integration
- ✓ Renewable Energy Integration Climate-Adaptive Systems
- ✓ Policy and Market Support

3 Digital Solutions and Biotechnology Advancements

Aquaculture is a vital part of global food security, but the more cost of feed, accounting for fifty-seventy percentage of total production expenses, hinders growth and sustainability (Solomon *et al.*, 2025). The reduction of wild fish stocks is straining the aquaculture sector, requiring innovation for sustainability. Digital transformation, including Internet of Things (IoT), Artificial intelligence (AI), cloud-edge computing, machine learning, and blockchain, can help meet industry expansion needs. Connecting digital Innovation Hubs can mitigate risks like pandemics (Rowan, 2023). Quality assessment technologies, feed formulation, and smart feeding technologies are being developed to reduce costs, enhance fish health, lower environmental impacts, and support sustainable global food production. These advancements are shaping the future of aquaculture nutrition (Solomon *et al.*, 2025). Innovations in feed technology, such as sustainable alternatives, advanced processing methods, and automated systems, are being developed to improve efficiency and sustainability (Nwankwo *et al.*, 2025). Advanced genetic techniques marker has improved fish breeding and nutrition. Molecular markers and cryopreservation technology protect endangered species and produce sterile fish (Maurya *et al.*, 2025). Biotechnology is transforming seafood processing, boosting the global market to USD 730.28 billion by 2030. It promotes zero-waste economy, sustainable production, and recovery of nutritional compounds from byproducts (Vijayan *et al.*, 2025).

Besides, Machine Learning and Computer Vision are some AI technologies that can access large data volumes collected from fish farms to provide informative patterns on growth, feeding behavior, and environmental factors that affect fish health (Mandal & Ghosh, 2024). The future of AI is going to be in the management and conservation of fish genetic resources (Singh *et al.*, 2024). AI monitoring networks collect real-time data on temperature, oxygen levels, fish behavior, and water quality for farmers to make suitable corrections (Panda *et al.*, 2025). The stacking ensemble learning model improves fish disease detection and risk assessment, attaining 87.7% precision and 85% accuracy in disease risk identification and prediction (Yasruddin *et al.*, 2025). Diseases like red spot disease represent a grave threat to aquaculture. Advanced technologies have been suggested as a remedy to uphold sustainable practices (Thakur *et al.*, 2024).

Recent advances in information technology, covering a broad spectrum of mobile applications, software, and artificial intelligence, have transformed, preventing, diagnosing, and treating diseases (Rathinam *et al.*, 2025). Fish-Sense is a deep-learning-based operational pipeline that collaborates with aquaculture farming for the improvement of disease detection and biomass estimation in fish farming. Fish-Sense efficiently classifies healthy and unhealthy fish (Aftab *et al.*, 2024). Key AI algorithms like Naive Bayes, Support Vector Machines (SVM), Deep Learning, and Artificial Neural Networks are evaluated for their practical integration into intelligent systems (Kilinc *et al.*, 2025). SVM are effective in determining optimal nitrogen application rates and identifying stress during crop growth, enhancing yield with timely interventions (Karimi *et al.*, 2006). Cloud computing, Internet of Things, and Artificial Intelligence (CIA) techniques like drones, nano-sensors, bionic robots, and algorithms can reduce human intervention and boost productivity (Mustapha *et al.*, 2021). From 2012 to 2023, there was a 70.5% increase in articles published on aquaculture technologies like AI, and sensors, highlighting their potential to enhance resource management, promote fishing, and meet nutritional needs (Capetillo-Contreras *et al.*, 2024). Artificial vision and machine learning are crucial in aquaculture, enabling data extraction and management.

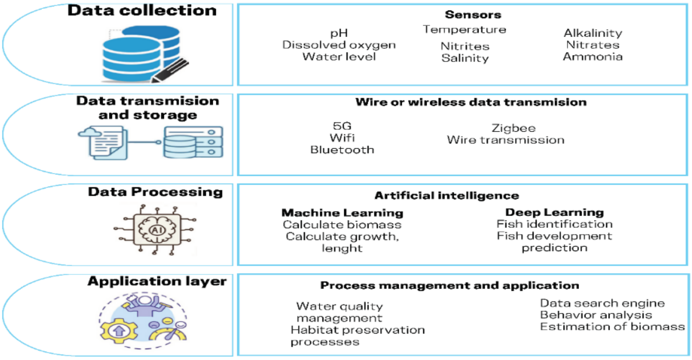


Figure 1. Demonstrates the use of data processing, transmission, and sensors in a variety of aquatic system operations

{**Source:** Capetillo-Contreras *et al.* (2024)}

Integrated farming systems optimize aquaponics with automatic sensor cleaning and real-time monitoring, promoting a zero-waste approach through the integration of various agricultural processes (Abidin *et al.*, 2024). Remote monitoring systems facilitate proactive management and prompt interventions (Nayoun *et al.*, 2024). IoT links physical devices, facilitating data gathering, distribution, and analysis via AI and machine learning, allowing for informed choices and enhanced operations without human involvement (Dupont *et al.*, 2018). Six essential criteria for efficient IoT networking in aquaculture: uninterrupted connectivity, swift data transmission, precise positioning, high dependability, comprehensive integration, and robust security protocols (Li *et al.*, 2020). The Fish Tank Management system, based on IoT, employs an Arduino Uno microcontroller to track pH, turbidity, and water levels, dispatch automated SMS alerts, and improve operational efficiency (Abidin *et al.,* 2024). Incorporating AI and IoT technologies in smart Biofloc technology (BFT) systems can enhance water quality, lower feed expenses, and boost fish health (Alghamdi & Haraz, 2025). Sensor technology in aquaculture is essential for real-time tracking and management of water quality factors, facilitating prompt identification of environmental shifts and informed decision-making, thereby enhancing efficiency and sustainability in aquaculture practices (Chelladurai *et al.*, 2024). The combination of intelligent sensor networks and IoT technologies is essential for improving productivity and sustainability in aquaculture (Liu *et al*., 2025). A smart aquaponic system powered by a Raspberry Pi microcontroller employs sensors to measure pH, temperature, turbidity, and perform ultrasonic monitoring. AI algorithms detect illnesses, assess biomass, enhance feeding plans, and deliver real-time monitoring (Abd *et al*., 2024).

The company has developed an IoT-based environmental control system for fish farms, utilizing machine learning algorithms (Random Forests, Support Vector Machines, Gradient Boosting Machines, and Neural Networks) to optimize environmental conditions, promote fish health, productivity, and resource efficiency, meeting global seafood demand while promoting environmental responsibility (Dhinakaran *et al*., 2023). Automated feeding systems optimize fish nutrition, reduce waste, and improve efficiency. Deep learning algorithms analyze feeding patterns, while IoT-driven innovations promote sustainable aquaponics systems (Selvaganesh *et al*., 2024). The integration of IoT in aquaculture faces challenges such as high initial costs, connectivity issues, cybersecurity risks, technical skill requirements, and maintenance concerns. It's more challenging for small-scale farmers to access, particularly in isolated regions with poor internet connectivity (Rahul *et al*., 2024). Models such as Decision Trees, Random Forest, and Linear Regression are employed to forecast aquaculture data, with Random Forest attaining the greatest accuracy (Gkikas *et al*., 2024).

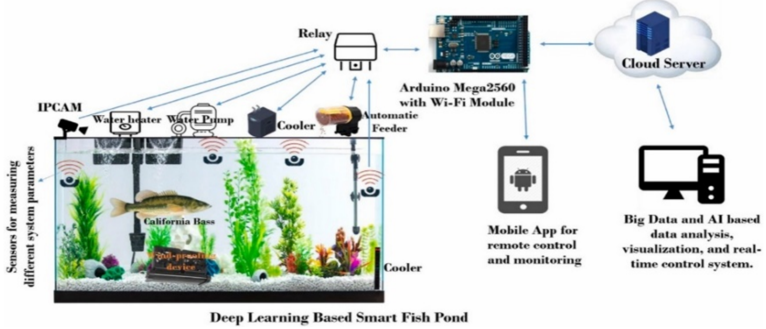


Figure 2. Design of an Intelligent Fish Pond Monitoring and Control System Using Deep Learning

{**Source**: Chiu *et al*. (2022)}

Remote Sensing (RS) is a discipline that employs electromagnetic radiation to recognize objects from afar, sensing their spectral signature, which is essential for visual interpretation (Subramani *et al*., 2017). This technology offers instantaneous data for species monitoring, oceanographic data analysis, and feeding schedule optimization (Ratan *et al*., 2025). RS necessitates an energy source, engagement with the atmosphere, interaction with the target, capturing energy, transmitting and analyzing data, and processing images (Subramani *et al*., 2017). Satellite remote sensing (SRS) plays an essential role in marine ecology, environmental oversight, and conservation efforts, offering high-resolution images for habitat analysis, ecosystem modeling, and detection of mesoscale features (Chassot *et al*., 2011). Aquaculture applications of Earth observation (EO) include species invasion modeling, planning, water quality monitoring, environmental impact assessment, and site selection (Soriano *et al*., 2019). Applications of SRS in fisheries offer social advantages, such as identifying fishing activity and assessing the impact of climate change on shrimp aquaculture, despite challenges with fisheries information systems (Saitoh *et al*., 2011). Potential technology transfer for sustainable fish farming was assessed (Subramani *et al*., 2017).

Genetic improvement through well-designed breeding programs and advances in sequencing and bioinformatics can help meet rising seafood demand. Combining genomic selection with biotechnological innovations may expedite genetic improvement (Houston *et al*., 2020). Aquaculture faces challenges like genetically improved species, disease-resistant feeds, and ecosystem pollution. Sequencing technologies revolutionize biological sciences, addressing these issues. Draft genomes have been published in 24 species, addressing breeding, diseases, and maturation (Yue & Wang, 2017). They detect overfishing, habitat loss, and environmental changes, enhance breeding programs, and guide restocking efforts, preserving aquatic biodiversity (Khatei *et al*., 2025). Genetic improvement through breeding enhances stocks, optimizing feed and land resources. Recent advances in fish breeding technologies, such as genomic selection and transgenesis, offer insights into the evolving field (Mushtaq *et al*., 2025).

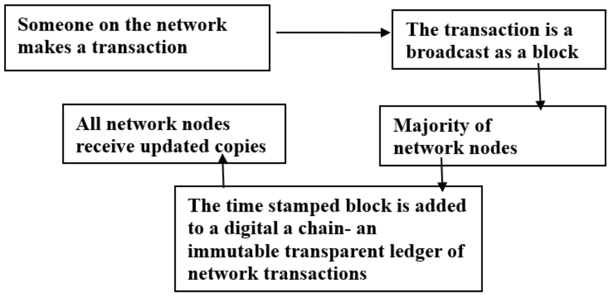


Figure 3. Traditional blockchain business workflow

{**Source**: Koçak *et al*. (2025)}

Biotechnology offers transformative solutions, improving sustainability, productivity, and resilience. Key applications include selective breeding, recombinant DNA vaccines, and probiotic-supplemented feeds (Andriani, 2025). Asian seabass, a resilient species, offers high market value and adaptability. Genetic advancements enhance traits, but further research is needed for disease prevention, climate resilience, and nutrition (Yue, 2025). Techniques like genetic engineering and hybridization are being employed to achieve sustainability and efficiency. However, factors like pollution and habitat loss must be considered in breeding programs (Devi *et al*., 2025). Genetic studies, including selective breeding and genome editing, are enhancing the durability and effectiveness of aquaculture species, making them quicker to grow and less susceptible to illnesses (Gjedrem & Baranski, 2021). For sustainability and adaptability, variation in genes must be retained (Huang *et al*., 2023). Supply chains for seafood could be revolutionized by blockchain technology, which would increase transparency, encourage responsible consumption, and help achieve the Sustainable Development Goals (Varriale *et al*., 2025). Traceability, preventing illicit fishing, quality assurance, certifications, and resource monitoring are just a few of the many advantages that blockchain technology brings to fisheries management.

It lowers the possibility of mislabeling and illicit fishing methods by providing a record of the product's journey (Koçak *et al.,* 2025). Blockchain technology can decrease fraud and food safety issues in the aquaculture industry by increasing transparency and traceability (Hisham *et al*., 2025). Data efficiency, sustainability, transparency, accurate data management, and stakeholder involvement are the main focuses of the blockchain-based framework being used to transform seafood supply chain management systems (Bharathi *et al*., 2025).

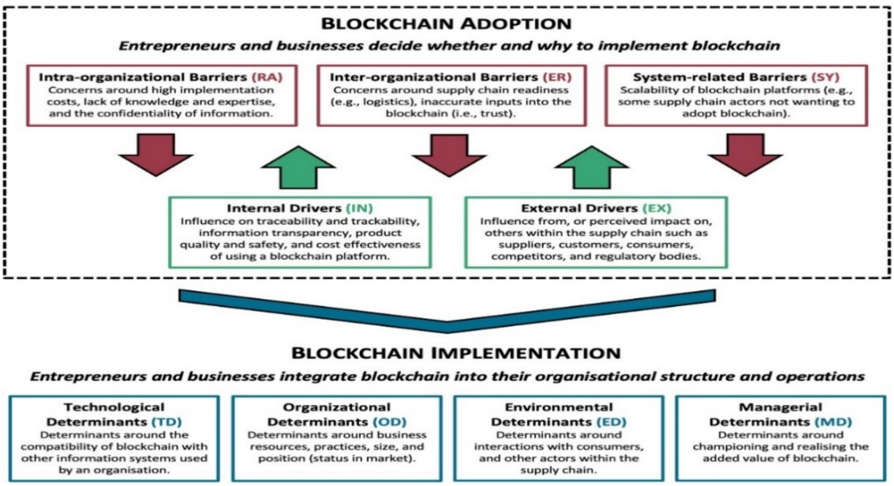


Figure 4. Factors impact the adoption and deployment of blockchain technology

Source: Thompson & Rust (2025)

4. Sustainable Feed Innovations and Resource Efficiency

4.1 Alternative Protein Sources and Circular Economy Approaches

By 2050, the world population is expected to reach nearly nine (09) billion people which will definitely increase pressure on sustainable development and this strain is driving the need for innovative food solutions to address its increasing demand. Globally, aquaculture has expanded significantly to address the increasing demand of food for exploding population (FAO, 2022; Naylor *et al.,* 2021). In order to fuel the rapid expansion of this vital sector, there is a dire need to transform aquafeed production into an environment friendly approach. Aquafeeds traditionally relied heavily on fishmeal and fish oil sourced from wild fisheries but these practices are now recognized as unsustainable and inefficient, therefore the industry is seeking alternative sources of protein (Fréon *et al.,* 2017). As a result, the industry is increasingly relying on such feeds that are based on the principles of circular economy and this approach involves more efficient use of resources, minimizing waste and improving environment (Cottrell *et al.,* 2020).

Researchers have discovered various novel protein sources in feeds such as plant meals, insect meals, single cell proteins, synthetic proteins, agricultural wastes and other alternatives, so the aquaculture industry is exploring these options in order to reduce its environmental footprint and enhances its sustainability (Shah *et al.,* 2018). In addition to reducing waste, circularity improves the resilience of aquaculture supply chains (Chew *et al.,* 2017) by diversifying input sources and reducing reliance on finite marine resources, thus contributing to long-term sustainability (Geissdoerfer *et al.,* 2017).

4.2 Microalgae, Insect-Based and Single-Cell Protein Applications

Scientists have found that microalgae, insect-based meals and Single Cell Proteins (SCPs) are promising as well as innovative alternatives to replace conventional seafood based ingredients in fish feed due to their nutritional quality, production potential and environmental sustainability (Makkar *et al.,* 2014) and they offer a range of benefits that make them attractive for use in aquaculture.

Microalgae are rich in protein, contain all essential amino acids and provide beneficial nutrients (Shah *et al.,* 2018). They do not require arable land or freshwater for cultivation, and some species can thrive on degraded lands and wastewater, thus being sustainable (Borowitzka & Moheimani, 2013). Insects can consume a wide range of materials, including manure and agro-industrial by-products, demonstrating the potential of waste valorization for food production (Oonincx & de Boer, 2012) and this ability makes them a valuable tool for reducing waste suggesting their suitability as partial substitute (Barroso *et al.,* 2014), Biotechnological advancements have made it possible to produce SCP by utilizing waste and green carbon sources such as industrial off-gas, agricultural residues and recycled materials, which have the potential to produce protein with minimal environmental impact and stable quality (Øverland *et al.,* 2010) so they are an attractive option for sustainable protein production.

4.3 Sustainable and Alternative Protein Sources:

The implementation of circular economy principles in aquafeed production involves several key methodologies:

Waste Stream Valorization: Waste streams can be upgraded and this can be achieved by processing agricultural waste streams. This can improve protein digestibility, removes anti-nutritional factors and improves palatability.

Industrial Symbiosis: Collaboration between aquafeed producers and food & beverage companies can help secure access to valuable waste streams.

Biorefinery Integration: Co-processing feed with biorefineries can increase the amount of protein recovered from crop residues.

SWOT Analysis - Enviro-Economic Perspective:

Strengths	**Weaknesses**	**Opportunities**	**Threats**
Reduced dependency on wild fish stocks, contributing to marine ecosystem conservation	Variable quality and availability of waste stream inputs	Growing consumer demand for sustainably produced seafood	Competition from other waste utilization sectors
Lower production costs through utilization of low-cost waste materials	Potential presence of anti-nutritional factors requiring additional processing	Government incentives for circular economy initiatives	Fluctuating prices of alternative raw materials
Enhanced resource efficiency and reduced environmental footprint	Need for significant investment in processing infrastructure	Technological advances in bioprocessing and fermentation	Potential contamination risks in waste streams

Creation of new revenue streams for agricultural and food processing industries	Regulatory challenges in approving novel feed ingredients	Potential for carbon credit generation through waste reduction	Consumer resistance to feeds derived from waste products

4.4 Microalgae, Insect-Based and Single-Cell Protein Applications

Microalgae based Protein:

Microalgae are considered an exceptional protein source due to their rapid growth rate, low resource requirements and high nutritional content, and some species such as *Chlorella vulgaris*, *Spirulina platensis,* and *Nannochloropsis* contain 40-70% protein on a dry weight basis.

Insect-Based Protein:

Insect farming has emerged as a highly efficient protein production system, with black soldier fly (*Hermetia illucens*) larvae and mealworms (*Tenebrio molitor*) leading commercial applications (Van Huis *et al.,* 2013; Makkar *et al.,* 2014).

Single-Cell Protein (SCP):

SCP production utilizes microorganisms including bacteria, fungi and yeast to convert various substrates into superior quality protein (Ritala *et al*., 2017).

SWOT Analysis – Microalgae, Insect, and SCP

Strengths	Weaknesses	Opportunities	Threats
High protein content and favorable amino acid profiles	High initial capital investment for production facilities	Growing market demand for sustainable protein alternatives	Competition from established protein sources
Rapid growth rates and high feed conversion efficiency	Technical complexity requiring specialized knowledge and equipment	Technological advances reducing production costs	Potential disease outbreaks in production systems
Minimal land and water requirements compared to conventional agriculture	Seasonal variations in production for some systems	Government support for alternative protein development	Energy cost fluctuations affecting production economics
Ability to utilize waste substrates, supporting circular economy principles	Consumer acceptance challenges, particularly for insect-based products	Integration with waste management systems	Regulatory restrictions on novel feed ingredients
Lower greenhouse gas emissions compared to conventional protein sources	Regulatory approval processes for novel protein sources	Potential for local production reducing transportation costs	Market volatility affecting investment returns

4.5 Reducing Wild Fish Dependency: Beyond Fishmeal and Fish Oil

The aquaculture industry's historic dependence on fishmeal and fish oil has created significant sustainability issues with approximately 70% of global fishmeal and 75% of fish oil production utilized in aquafeeds leading to cost related and environmental challenges. The *Fish In:Fish Out* (FIFO) ratio for major aquaculture species ranges from 0.2-5.0 indicating high degrees of wild fish dependency.

4.5.1.1 Alternative Protein Development:

4.5.1.2 Plant-Based Protein Sources:

Soybean Meal processing includes advanced processing techniques including fermentation, enzyme treatment and protein concentration reduce anti-nutritional factors while improving digestibility (Boye *et al.,* 2010) while Canola/Rapeseed Meal involve solvent extraction followed by heat treatment and enzyme supplementation improves protein quality and reduces glucosinolate content (Khajali & Slominski, 2012).

4.5.1.2 Processed Animal Proteins (PAPs):

- ✓ **Poultry By-Product Meal:** Rendering processes at temperatures exceeding 133°C for minimum 20 minutes produce high-quality protein meals with 60-70% protein content.
- ✓ **Hydrolyzed Feather Meal:** Pressure cooking and enzymatic hydrolysis improve amino acid availability, particularly cysteine and methionine content.

4.5.1.3 Fish Oil Alternatives:

Algal Oil Production:

Heterotrophic Cultivation involves *Schizochytrium* and *Crypthecodinium* species produce oils rich in DHA (docosahexaenoic acid) through fermentation processes, achieving oil contents of 50-77% dry weight (Barclay *et al*., 2010) and **Photosynthetic Production** invloves *m*arine microalgae cultivation produces EPA (eicosapentaenoic acid) and DHA through photobioreactor systems with productivities of 10-50 mg/L/day.

SWOT Analysis - Wild Fish Dependency Reduction:

4.6 Functional Feed Additives and Life Cycle Assessment of Ingredients

Strengths	**Weaknesses**	**Opportunities**	**Threats**
Reduced pressure on wild fish stocks supporting marine conservation	Amino acid imbalances requiring supplementation	Consumer demand for sustainably produced seafood	Competition from other sectors for alternative protein sources
Price stability through diversified ingredient sourcing	Presence of anti-nutritional factors affecting fish performance	Technological advances in ingredient processing	Regulatory restrictions on novel ingredients
Improved feed security through reduced dependency on marine resources	Lower palatability compared to fishmeal-based diets	Development of novel protein sources	Consumer resistance to modified production methods
Enhanced sustainability credentials for aquaculture products	Potential reduction in omega-3 fatty acid content of farmed fish	Government incentives for sustainable aquaculture	Price volatility of alternative raw materials
Potential for local sourcing reducing transportation costs	Higher processing costs for some alternative ingredients	Potential for premium pricing of sustainable products	Potential negative impacts on fish health and performance

4.6.1 Functional Feed Additives:

Functional feed additives represent a paradigm shift from basic nutrition toward precision aquaculture, incorporating bioactive compounds that enhance fish health, growth performance, and stress resistance (Gatlin III *et al*., 2007).

Categories and Production Methods:

1. Prebiotics:

Prebiotics are non-digestible feed ingredients that selectively stimulate beneficial gut microbiota growth.

2. Probiotics:

Live microorganisms that confer health benefits when administered in adequate amounts.

3. Immunostimulants:

Compounds that enhance innate immune responses in fish.

4. Phytogenic Compounds:

Plant-derived compounds with antimicrobial, antioxidant and growth-promoting properties.

SWOT Analysis - Functional Additives and LCA:

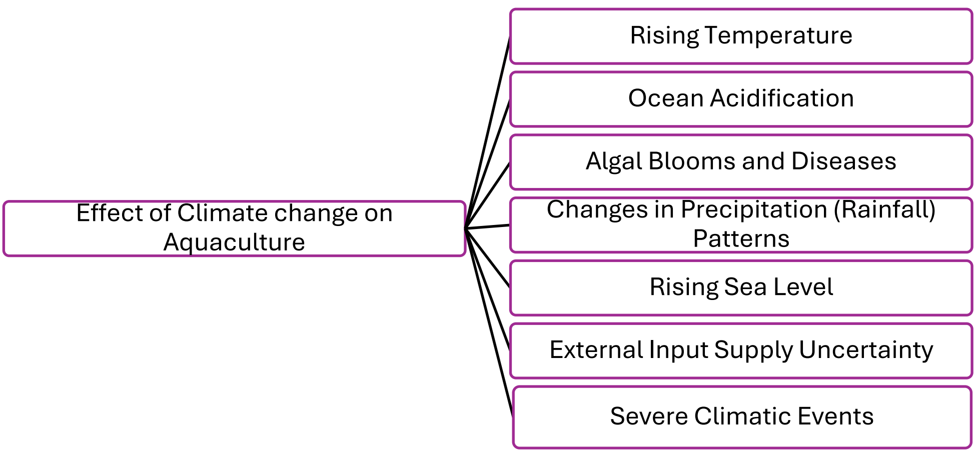
Strengths	Weaknesses	Opportunities	Threats
Enhanced fish health and performance reducing medication needs	Higher production costs for functional additives	Growing consumer awareness of sustainable production	Regulatory restrictions on novel additives
Improved feed conversion efficiency reducing environmental impact	Complex regulatory approval processes	Regulatory support for antibiotic alternatives	Competition from pharmaceutical alternatives
Scientific basis for environmental impact assessment through LCA	Variable efficacy depending on species and production conditions	Technological advances reducing production costs	Consumer skepticism regarding feed additives

5 Climate Resilience and Biodiversity Conservation

Aquaculture is currently the fastest-growing food production sector in the world due to its continued considerable production expansion. However, the anticipated consequences of climate change, which are both a future and a current reality, put the sector's viability in jeopardy. Due to the use of fossil fuels (coal, oil, and gas) for energy supply (Palmer and Stevens, 2019) and deforestation and forest degradation (Riphah, 2015), which release greenhouse gases (GHGs) into the atmosphere, humans are known to be the primary cause of climate change.

5.1. Climate Change's Impact on Aquaculture and Its Consequences for Sustainability

Aquaculture productivity is anticipated to be impacted by climate change in both direct and indirect ways. One of the main challenges facing the sustainability of food production systems is climate change, and aquaculture is no exception. The effects and solutions of climate change are closely related to sustainable development, which strikes a balance between social well-being, economic prosperity, and environmental preservation.



5.1.1 Rising Temperature

Aquatic species' growth and development are greatly influenced by temperature. Because they are poikilothermic, fish might be especially vulnerable to changes in temperature brought on by climate change (Adhikari *et al.*, 2018). Since the average world temperature is expected to rise by 1.5°C this century, most fish, particularly cold-water species like Atlantic halibut, salmon, and cod, as well as intertidal shellfish, would likely experience higher mortality rates as a result of thermal stress (Gubbins *et al*., 2013). As a result, extended temperature stress may have a variety of effects on aquaculture productivity, with decreased output being the main one. The neuroendocrine and osmoregulatory systems, for instance, may be impacted by prolonged stress, changing the aerobic range and cardiorespiratory function as well as the immunological responses of a number of commercially significant species.

5.1.2 Ocean Acidification

Ocean acidification is the outcome of atmospheric CO_2 absorption causing the pH levels of ocean water to drop over a long period of time (sometimes decades. Water may become more acidic (pH reduction) as a result of increased CO_2 concentration. Additionally, when ocean acidity rises, less carbonate is available for shell-forming creatures like shrimp, mussels, oysters, and corals to build their skeletons (calcification), which could endanger the productivity of marine farming. The production of wild spat oysters, for instance, may decrease as a result of higher juvenile predation rates after inadequate coral skeleton construction, which reduces collecting rates (Blanchard *et al*., 2017).

5.1.3 Algal Blooms and Diseases

A changing temperature regime is anticipated to have an impact on aquaculture diseases, including bacterial, parasitic, viral, and fungal infections, albeit the effects will be mostly unpredictable. But there is little doubt that exposing to thermal stress conditions makes cultured organisms more prone to disease, and that greater temperatures may lead to the emergence of exotic diseases. Additionally, it is anticipated that warm water pathogens, such sea lice, would continue to be a problem for salmon farming, and that additional warming will probably make illnesses worse in colder climates, necessitating more treatments and higher costs.

5.1.4 Changes in Precipitation (Rainfall) Patterns

Changes in rainfall patterns will have two opposing effects on aquaculture output and sustainability: periods of low or no rainfall (drought) and increasing rainfall (flooding). The IPCC (2018) states that while patterns of flooding events are hard to anticipate with precision, risks from drought events are likely to be higher at 2°C of global warming in a given location than at 1.5°C. The production risks in lowland areas will rise with increased rainfall, especially if it happens during bigger events (Bell *et al*., 2009). These hazards include fish being lost from ponds during floods, unwanted species invading ponds, and pond damage from infilling and wall washing (Rutkayova *et al*., 2017).

5.1.5 Rising Sea Level

According to IPCC (2018) forecasts, sea level rise will be about 0.1 meters lower under 1.5°C global warming than under 2°C by 2100. Nonetheless, it is anticipated that this increase will persist into 2100, with the extent and pace of this increase most likely relying on the future GHG routes. Sea level rise has the potential to wipe out a number of coastal ecosystems, including salt marshes and mangroves, which are thought to be essential for preserving wild fish supplies and providing seed for aquaculture production.

5.1.6 External Input Supply Uncertainty

The main external input sources for aquaculture production are agriculture and capture fisheries, indicating a close connection between these two sectors. Aquaculture is a complementing activity to capture fisheries, and while it practices more like agriculture, it has significant connections to capture fisheries, according to Cochrane *et al.* (2009). In general, it is anticipated that the effects of climate change on agricultural and capture fisheries will reduce the supply and raise the price of inputs like fish seed and feed ingredients needed for aquaculture development.

5.1.7 Severe Climatic Events

Aquaculture development, particularly for marine ornamental items and those in coastal settings, is anticipated to be impacted by severe weather events including storms, waves, and cyclones. Farmers of coral and giant clams in tropical villages, for instance, might be more vulnerable to bleaching-related losses, whereas those in sub-tropical areas are more likely to experience more severe risks, like losing their stock and production equipment as a result of rougher seas brought on by stronger cyclones.

5.2 Adaptations to the climate change

Because it provides producers with options for generating their income and enabling them to develop suitable resilience to the effects of climate change, livelihood diversification may be one of the keys to successful adaptation (Zolnikov, 2019). It entails integrating or separating aquaculture production systems with those of other industries, like agriculture. Diversifying sources of income is quite beneficial, particularly in certain areas or nations where agricultural production is forecast to rise but fish production is predicted to fall (Blanchard *et al*., 2017). However, for diversification to be successful, government policies must offer incentives for equitable resource use, environmental protection, and efficient resource use (Troell *et al*., 2014). Switching to aquaculture species, methods, or regions that are less susceptible to or more adaptable to a changing environment and resources may also be advantageous for aquaculture producers (Lim-Camacho *et al*., 2015).

Building adaptive capacity in aquaculture, particularly for small-scale producers through insurance programs, is another expanding area that may be taken into consideration for adaptation. Due to their limited ability to adapt, small-scale producers are expected to be the most impacted by climate change, according to the majority of projections (Barange *et al*., 2018).

5.3. Carbon Footprint Reduction in Aquaculture Sector

Countries everywhere must work together to address the pressing issue of climate change. The effects on the carbon cycle and carbon balance have received more attention since the 1997 publication of the Kyoto Protocol. It was suggested that the world temperature could rise by more than 2°C by 2030 if greenhouse gas (GHG) emissions are not drastically reduced.

5.3.1 Carbon Footprint

The entire quantity of greenhouse gases generated throughout the course of a person, business, or product's life cycle is known as the carbon footprint. Metric tons of carbon dioxide equivalent (CO_2) are commonly used to quantify the carbon footprint. But it's important to remember that other greenhouse gases, such as nitrous oxide (N_2O) and methane (CH_4), also contribute significantly to climate change.

5.4. Factors that influence aquaculture production's carbon footprint

Meeting the demand for aquatic products worldwide depends heavily on aquaculture. The production and consumption of feed contribute significantly to greenhouse gas emissions, making up a sizable portion of all emissions during cultivation. Aquaculture sites' fuel and energy consumption are also major sources of emissions.

- ✓ Specie culturing
- ✓ Shape and size of aquaculture farms
- ✓ Different types of feed
- ✓ Management of diseases
- ✓ Controlling water quality parameters
- ✓ Energy utilization

5.5 Methods to Decrease Carbon Emissions from Fisheries

Activities including fishing, navigation, aquaculture, and processing all contribute to the carbon footprint of fisheries, which calls for industry-wide reductions. Operational strategies to lower carbon emissions in fishing are given below.

- ✓ Practice sustainable fishing methods
- ✓ Processing aquatic products before exporting can lead to greenhouse gas emission reduction of 5-30%.
- ✓ Protect the marine ecological environment.
- ✓ Recycle waste materials and refrain from discarding refuse into the marine environment.

5.6 Biodiversity Conservation in Aquaculture Zones

Aquaculture can be broadly divided into three categories: intensive, which primarily relies on nutritionally complete concentrate feed and fertilizers; semi-intensive, which has some additional feed and/or fertilizers; and extensive, which has no feed or fertilizer inputs and relies on natural food produced in the water body. Aquaculture, particularly intensive systems, has been found to have a number of biophysical effects on ecosystem services and biodiversity. These effects are typically unfavorable, however they can also be neutral at times. Both direct and indirect effects are possible, such as habitat loss or genetic modification of current fish species. Among these effects are:

- ✓ Loss and alteration of habitat, including wetlands and mangroves;
- ✓ Availability of fresh water;
- ✓ Local water pollution leading to eutrophication of water bodies, effluents, and alterations in the fauna of receiving waterways;
- ✓ Aquatic crops' escape and the possible threat they pose as invasive species;
- ✓ Thorough gathering of wild seeds;

5.6.1 Aquaculture's Social and Economic Impact on Biodiversity

Many environmental services that biodiversity offers are essential to human well-being both now and in the future. The activities or functions of ecosystems that are valuable to people or society are known as ecosystem services. These services are:

- Cultural services are the intangible advantages that humans derive from ecosystems through cognitive growth, spiritual development, contemplation, leisure, and aesthetic experience, which includes social relationships, knowledge systems, and aesthetic ideals.
- Products derived from ecosystems, such as fresh water, food and fiber, and genetic resources, are examples of providing services.

5.7 Ecosystem Based Management Framework for Aquaculture

A complete strategy that combines ecological, social, and economic objectives to guarantee aquaculture is sustainable, reduces environmental effects, and promotes ecosystem health is known as an Ecosystem-Based Management (EBM) Framework for Aquaculture.

1. Define the Ecosystem and Scope

- Determine the biological borders, such as the maritime zone, watershed, and coastal area.

- Incorporate all elements of the ecosystem, such as species, habitats, water quality, and human activity.
- Establish precise time and space limits for management.

2. Establish Integrated Objectives and Goals

- Ecological objectives: preserve ecosystem functions and biodiversity.
- Social objectives: uphold community values and sustain local livelihoods.
- Economic objectives: encourage long-term profitability and sustainable industry expansion.

3. Participation of Stakeholders

- Involve local communities, NGOs, industry, scientists, policymakers, and fishermen.
- To foster trust and collect a range of viewpoints, use participative tactics.

4. Develop Resilience

- Be ready for the effects of climate change, such as acidity and warming of the oceans.
- Diversify systems and species (integrated multi-trophic aquaculture, or IMTA, for example).
- bolster communities' socioeconomic resilience.

5. Evaluation of Impact and Risk

- Examine the effects on the environment, such as invasive species, habitat damage, and nutrient loading.
- Keep an eye on the economic and social impacts.
- Make use of resources such as Life Cycle Analysis (LCA) and Environmental Impact Assessments (EIAs).

6. Zoning and Spatial Planning

- Aquaculture zones should be chosen according to carrying capacity and ecological sensitivity.
- Avoid locations that overlap with conventional fishing zones, protected areas, and important fish habitats.

7. Management That Adapts

- Utilize monitoring data to make necessary practice adjustments.
- Use feedback loops to gain knowledge and get better over time.
- React promptly to emerging risks or scientific findings.

8. Coordinated Tracking and Reporting

- Monitor disease outbreaks, feed consumption, benthic effects, water quality, etc.
- Inform stakeholders of findings on a regular basis.
- Assure accountability and openness.

9. Alignment of Policy and Regulation

- Organize across industries (tourist, conservation, and fishing).
- Make sure that ecosystem-based principles are supported by laws and regulations.
- Comply with international and regional frameworks (such as the FAO Code of Conduct).

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CHAPTER XI

SUSTAINABLE FISHERIES MANAGEMENT IN RESERVOIRS: STRATEGIES FOR OPTIMIZING INLAND AQUACUL TURE IN TUNISIA[56]

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Introduction

With two coastlines spanning 1,350 km, a national maritime domain of 80,000 km² and 105,200 hectares of lagoons, Tunisia has a longstanding heritage as a maritime nation. Consequently, fisheries and aquaculture have consistently been a sector of significant economic and social importance (Romdhane et al., 2019). This strategic industry accounts for 8% of the value of agricultural production and 1.1% of the gross national product, while generating around 53,000 direct jobs (DGPA, 2023). The national development strategy for this sector is based on preserving benthic resources, exploiting small pelagic species, adding value to commercial fishery products and developing aquaculture in targeted areas.

However, Tunisia has experienced mounting pressure on its marine fishery resources for several years, evidenced by a decline in coastal and bottom trawl production. This trend has persisted despite the total national catch stabilising at around 100,000 tonnes per year (DGPA, 2023). In this context, aquaculture emerges as an indispensable alternative to offset the deficit in marine fishery products to some extent. The sector has demonstrated remarkable growth, with production soaring from 1,615 tonnes in 1999

(DGPA, 2000) to 9,994 tonnes in 2014 and 25,000 tonnes in 2021 (DGPA, 2023). This production encompasses both marine and inland aquaculture.

The use of dam reservoirs for aquaculture purposes dates back to the 1960s (Miliet al., 2015a; Laouar, 2019) and was initiated by the National Fisheries Office (ONP) through the stocking of various species (Losse et al., 1992). Despite this early start and the existence of significant water resources, the development of inland aquaculture has remained limited. Until the late 1980s, activities were confined to the sporadic stocking of reservoirs or small hill lakes (Mili et al., 2021a; Mtimet, 2010), and only a few species, such as common carp (*Cyprinus carpio*) and tilapia (*Oreochromis niloticus*), successfully acclimatised (Mili et al., 2015a; Laouar, 2019). A significant milestone was reached in the early 1990s with the Tunisian-German cooperation project “on the use of dam reservoirs for freshwater fish farming”, which introduced freshwater fish into Sidi Salem reservoir, the country's largest drinking water reserve, and established the foundations for modern aquaculture in Tunisian reservoirs (Chargui et al., 2025; Djemali, 2005).

The promising growth rates of the introduced species, alongside the establishment of local operations by cooperatives and graduates, clearly demonstrate that reservoirs have significant untapped potential for sustainable food production. Nevertheless, the management of these fisheries continues to face substantial administrative and technical challenges. The absence of a reliable system for collecting production statistics severely hinders the development of this sector. Furthermore, despite state efforts, production levels consistently fall short of the targets set out in various economic and social development plans.

Within this framework, a convention was established between the Higher Institute of Marine Sciences of Bizerte (ISSMB) and the Technical Aquaculture Centre (CTA) to address these gaps through targeted research and development (Mili, 2017; Mili et al., 2021a). The work conducted under this agreement comprises two main components:

1) A comprehensive diagnosis of the current state of inland aquaculture in Tunisia, involving:

- assessing the technical and socio-economic status of operations through focused surveys;

- Evaluating the status of fish communities in reservoirs.

- Analysing the population dynamics of key freshwater fish species.

- Conducting an Ecotoxicological study of selected freshwater fish species.

2) The development of strategies for exploiting fish resources in reservoirs, focusing on three areas:

- Optimising stocking and fingerling collection techniques.
- Improving techniques for the exploitation and propagation of freshwater fish resources;
- Enhancing fish harvesting methods in freshwater reservoirs.

This chapter presents the findings and strategies derived from this research to contribute to the sustainable and optimised management of Tunisia's inland aquaculture potential.

Section 1: Diagnosis of the current state of inland aquaculture in Tunisia.

I. Technical and socio-economic survey of the aquaculture sector in Tunisian reservoirs

1. Research context and objectives

Research on inland aquaculture in Tunisia is limited and fragmented. The existing literature has primarily focused on the ecobiology of specific freshwater fish species (Kraim, 1994; Toujani, 1998; Djemali, 2005) and on biomass assessments using acoustic methods (Djemali et al., 2009; Djemali et al., 2010). The pioneering work of Losse et al. (1992) and Mtimet (2010) is are rare exception in that they address sector development directly. In light of this significant data gap and the absence of reliable statistics, this research aims to develop the inland aquaculture sector through systematic surveys and interviews with industry professionals.

2. Materials and Methods

A comprehensive diagnosis of Tunisia's inland aquaculture sector was conducted through structured surveys and in-depth interviews with a variety of stakeholders. Data collection encompassed key parameters related to reservoirs, fishing effort, production levels and, crucially, the technical specifications of fishing gear and prevailing operational challenges. A diagnostic analysis was performed to compare different modes of fish exploitation in reservoirs and analyse the sector's overarching operational environment (Mili, 2017).

The study focused on 14 waterbodies in northern and central Tunisia, chosen based on factors such as reservoir capacity, surface area, number of active operators, and exploitation methods, to ensure a representative sample.

3. Key findings

All the data collected were systematised and entered into an interactive database. This database was then disseminated to the relevant administrative and research institutions involved in inland aquaculture. These include the Interprofessional Group of Fishery Products (GIPP), the General Directorate of Fisheries and Aquaculture (DGPA), the Technical Centre of Aquaculture (CTA), the National Institute of Marine Sciences and Technologies (INSTM), the Regional Commissariats for Agricultural Development (CRDA), the Agency for the Promotion of Agricultural Investments (APIA), the General Directorate of Veterinary Services (DGSV), and the Agency for Agricultural Extension and Training (AVFA).

The key findings, organised thematically, are summarised below:

3.1. Operator profile and demographics

The workforce is exclusively male (100%), with 73% of operators being married. Spouses often assist with net mending. A significant proportion (45%) is aged 35–45, indicating that the activity attracts a relatively young demographic, which bodes well for its long-term sustainability. Education levels are modest: 48% have completed primary education, 39% have completed secondary education, and 11% are illiterate. This profile suggests a capacity for adopting new techniques (Mili, 2017).

Most operators (70%) are natives of their operating regions, and 75% are enrolled in the national social security system (CNSS). Seventy per cent have over 15 years' experience, highlighting their commitment and expertise. For 90% of operators, aquaculture is their sole source of income, highlighting its critical socio-economic role. Operator mobility is low, with 72% having never changed reservoirs, indicating stable local employment. Only 37% have a background in marine fishing. Most (80%) work in pairs as regulations limit boat crews to two people (Mili, 2017).

Partnerships are predominantly based on equal profit-sharing (50/50) (63%), often among relatives. Most people work the entire authorised 10-month season, losing an estimated two months annually to bad weather. The mandatory two-month closure (March–April) is used for boat and net maintenance, but it represents a significant loss of earnings and forces many to seek temporary alternative work. Daily working hours exceed seven hours for 48% of operators. Production levels are highly variable and depend on reservoir characteristics, the number of operators and individual skill (Mili, 2017).

The organisational structure of the Fisheries and Aquaculture Development Groups (GDPs) is uniform. The presidents are usually experienced, active fishers who are native to the region. Other board members are also operators with no formal GDP roles. GDP activities largely consist of collecting fees for stocking operations and liaising with regional authorities.

The promoters, who are aged 30–40, all hold university degrees in aquaculture and have received entrepreneurship training. Unlike local fishers, they are not native to the reservoir regions, and they hire local labour for fishing operations.

3.2. Fishing Gear and Operational Infrastructure

Compared to marine aquaculture, the equipment is rudimentary and is typically limited to a non-motorised wooden boat (owned by 86% of operators; 4.5–6 m in length), fishing nets, crates and coolers (Mili, 2017). Promoters operate two similar boats.

Gillnets are the dominant type of net (61%), with trammel nets, combined nets and longlines being used less frequently. Some promoters also use fyke nets for eels. Operators favour gillnets for mullet and pikeperch, while trammel nets are used for catfish. Combined nets are rare (13%) due to their complex assembly, despite their high efficiency. Most nets (57%) are made of 0.28 mm monofilament. The depth of gillnets varies (100, 150, 200 and 300 meshes), with 100 meshes being the most common. The number of floats (50–80 per net) and their size (65–70 mm, most common at 43%) are highly variable, which compromises catch efficiency. Weighting is also inconsistent (75–320 weights per net). Most nets (64%) are rigged with polypropylene lead lines and polyethylene headlines. The cordage diameter is typically 6 mm for headlines (79%) and 5 mm for lead lines (54%) (Mili, 2017).

The two main fishing techniques employed by 61% of operators are overnight sets in winter and active bank encirclement in summer, aimed at ensuring freshness.

The number of crates varies significantly by reservoir and operator. Over half of the operators in Sidi Saad have 10–15 crates (Hajlaoui et al., 2022), whereas 58% of those in Sidi Salem have fewer than 10. Fish are primarily transported (84%) in unrefrigerated vans with ice in coolers. Most operators rent vans individually or collectively. In Sidi Salem, motorcycles are the main means of transport (58%). GDPs possess basic storage infrastructure, with the groups in Sidi Salem being the best equipped; the Seliana group has none. The Sidi Saad group uses private freezers (Mili, 2017; Hajlaoui et al., 2022). Promoters have superior logistics, including cold storage, insulated boxes and dedicated vans.

3.3 Exploited species

The diversity of species caught varies by reservoir, but mullet (*Chelon ramada* and *Mugil cephalus*) and carp (*Cyprinus carpio* and *Hypophthalmichthys molitrix*) dominate, collectively constituting 77% of the national inland catch. Barbel and catfish account for around 15%, while rudd, eel and tilapia make up a smaller proportion. Eel and catfish catches are low and incidental due to suboptimal techniques. *Mugil cephalus* is reported as the most challenging species to catch, followed by catfish (Mili, 2017).

3.4. Value Chain

Most operators (67%) sell directly at the Tunis wholesale market, and 83% also sell to GDPs. Some of the catch is consumed locally or sold in nearby villages. The highest market demand is for mullet (87%) and pikeperch (65%), followed by catfish (25%) and carp (13%). Eel is highly prized, with demand peaking seasonally (Mili, 2017).

Prices fluctuate based on species, reservoir, season and demand. There are two main types of vendors: mobile vendors who specialise solely in freshwater fish for local, lower-income markets (operating within a 20 km radius) and fishmongers who handle both marine and freshwater species for a broader clientele (operating within a 50 km radius), including coastal hotels. Fishmongers, who are often former operators, are the most experienced traders (Mili, 2017).

Premium species, such as mullet, pikeperch, and eel, command prices of 3.5–5.5 DT/kg, 3.5–6.5 DT/kg, and 6–12.5 DT/kg, respectively. Silver carp fetch a significantly higher price than common carp, at 4 DT/kg and 0.5 DT/kg, respectively. Promoter incomes average 40,000 DT per year. Direct purchase from fishers is the most common consumer practice (46%). Consumers are highly aware of the most common species, which are mullet (36%), pikeperch (31%), eel (26%), catfish (17%) and carp (12%) (Mili, 2017).

3.5. Consumption patterns

Most respondents (72%) consume freshwater fish, categorised as regular, moderate, occasional or sporadic consumers. In northern Tunisia, freshwater fish constitute 47% of household fish consumption. The most commonly consumed species are mullet (70%) and pikeperch (60%), followed by carp (24%), catfish (16%), and eel (14%). The primary methods of preparation are frying (53%) and grilling (37%). Freshness (25%) and proximity of sales points (23%) are the main factors influencing purchases. Conversely, taste (38%), lack of habit (21%) and smell (11%) are the main barriers to consumption (Mili, 2017).

4. Critical challenges

Despite state efforts, the sector is facing stagnation with a production of 1,000 tons per year versus a forecast of 2,400 tons for 2016 and only 690 tons in 2023. The lack of a reliable production statistics system is a major impediment to development (Mili, 2017).

Following the revolution, many young promoters withdrew. Profitability has been undermined by increased illegal fishing, weak enforcement and local operators' resistance to external promoters. Nearly half (42%) of operators work clandestinely without valid permits.

A fundamental constraint is the reliance on natural fry collection to stock species that cannot reproduce in reservoirs, such as mullets, eels and Chinese carps. This makes production highly dependent on rainfall, threatens wild mullet stocks and risks bans. Urbanisation and dam construction have reduced the number of viable fry collection sites.

Ineffective control systems exacerbate illegal fishing and environmental degradation. GDPs often fail to fulfil their core roles as negotiators, facilitators of equipment and mediators of conflict. Only 45% of operators comply with the eight-net limit; some use over thirty. Half of those interviewed admitted to ignoring the closed season due to economic precarity (Mili, 2017).

There are many technical inefficiencies. The prevalent use of an 80% hanging ratio reduces mesh opening and efficiency, while poor net rigging increases costs. The use of non-regulation mesh sizes and disregard for seasons leads to the overexploitation of resources. Overreliance on gillnets stems from a lack of skill with other equipment.

Operators report a variety of major difficulties, including lack of equipment (48%), conflict/theft (27%), adverse weather conditions (22%), marketing issues (21%), low catch rates (21%), transport issues (16%), lack of ice (14%), poor access to credit (11%), and inadequate refrigeration facilities (13%). Access to credit is the main barrier to acquiring adequate transport (Mili, 2017).

Boats and nets represent the primary capital investment. Nets require annual replacement. 95% of operators received no subsidy for renewing their gear, citing either bureaucratic complexity or unawareness. Banks universally deem the sector uncreditworthy. Conversely, promoters accessed Tunisian Solidarity Bank (BTS) loans and start-up grants.

Despite earning above the minimum wage (SMIG: 6,339.84 DT), operators' earnings are low (3,700–6,720 DT per year) and irregular. This compels 52% of operators to seek a secondary source of income. Promoters have failed to secure supermarket contracts due to production irregularities. The absence of a health monitoring network prevents exports, despite there being foreign demand for pikeperch and silver carp. Currently, the market is limited to the Tunis wholesale market or low-cost local sales (Mili, 2017).

Sector development is overly dependent on national agencies (CTA and GIPP) for stocking, with minimal support from regional authorities. GDPs are poorly structured and led by presidents with low levels of education. They have also deviated from their mission into primarily profit-driven sales, creating a major institutional weakness. Poor communication plagues all operational aspects, including marketing and procurement. Price instability has a severe impact on incomes (Mili, 2017).

Inadequate infrastructure is compounded by unresolved land tenure issues near dams. Trophic imbalances can be caused by introducing carnivorous species or overharvesting herbivores and omnivores. The community is hostile towards outsiders. Operators receive no compensation for losses resulting from weather events or floods (Mili, 2017).

5. Strategic Recommendations

Developing a sustainable inland aquaculture sector in Tunisia requires a comprehensive, multifaceted strategy. First and foremost, governance and enforcement must be strengthened through enhanced surveillance to curb illegal and illicit fishing activities, including the use of mesh sizes that do not comply with regulations and disregard for closed seasons. Urgent reform of the Fisheries and Aquaculture Development Groups (GDPs) is essential to restore their original support functions, establish new groups at large reservoirs and require operator membership. The roles of all public institutions involved must be clarified, and joint action plans and a shared database must be developed to improve coordination. Furthermore, fixed, equipped surveillance posts with motorised boats must be established at dams in coordination with the General Directorate of Major Hydraulic Works (DGEGTH) during their construction to enable effective monitoring and control.

In terms of production and stock management, the sector should prioritise making better use of reservoirs by promoting the capture of high-value species such as mullet and eel for the domestic market, and carp and pikeperch for export. The development and implementation of standardised net usage schedules is crucial for improving efficiency and sustainability. To optimise fish communities, transfer programmes for pikeperch and forage fish to suitable reservoirs should be initiated. A fundamental shift from natural fry collection to hatchery production is required, involving the introduction of hatchery-produced Chinese carp and the implementation of systematic, annual stocking of mullet fingerlings. Science-based management must be underpinned by a rigorous assessment of fish stocks in all reservoirs to develop bespoke stocking and transfer programmes. There must also be mandatory quality control and survival rate assessments for all stocked fingerlings. Finally, supporting research-development projects for the artificial reproduction of key mullet species (*M. cephalus* and *C. ramada*) in hatcheries, as well as assigning the management of unexploited or new reservoirs to promoters for the intensive cage culture of Nile tilapia, represents significant growth opportunities.

The sector's human capital requires immediate and sustained investment. Training and support programmes should be prioritised, beginning with the allocation of operating permits to young, local people from disadvantaged backgrounds who have received training, to ensure community integration and sustainability. Regular technical, commercial and informational training for existing operators is vital for improving practices. Overcoming the fundamental constraint of limited access to credit and loans is essential to enable operators to acquire the necessary production and storage equipment. Additionally, organising specific training for operators' wives in net mending and processing value-added products could provide a vital secondary income stream and improve household resilience.

To unlock the sector's economic potential, a strategy focusing on marketing, added value, and exports is indispensable. The supply chain must be organised by regulating mobile vendors and specifying transport standards, while simultaneously upgrading fishmongers' operations to require refrigerated vans. Incentivising formal contracts between GDPs and hotels can secure stable markets. Most critically of all, establishing a health monitoring and traceability system that meets international standards is a prerequisite for accessing lucrative export markets. Investment in processing units for cleaning, gutting, drying, salting and smoking can create valuable, export-ready products. To stimulate demand, promotional and tasting events for hoteliers should be organised, and sport fishing should be developed in hill lakes to attract tourism and diversify revenue streams.

Finally, this development must be backed by tangible investment in infrastructure and financial support. Promoting dedicated equipment and accessory shops in cities near reservoirs would improve access to the necessary gear. It is essential to build operator premises with freezing capacity for proper storage and to reduce post-harvest losses. Proper landing sites must be created at dams during their construction, in coordination with the DGEGTH, to enable accurate catch monitoring. Ultimately, the establishment of a dedicated development fund for inland aquaculture is recommended to provide sustained financial support for these wide-ranging reforms.

In conclusion, a comprehensive action plan is required that addresses the technical development of the sector and the social promotion of its professionals. This involves improving working conditions, providing targeted training and fundamentally reframing the role of GDPs to empower them in their mandated missions. This will ensure the sustainable and optimised management of Tunisia's inland aquaculture potential.

II. The status of fish communities in Tunisian reservoirs

1. Research context and objectives

Tunisian inland aquaculture shows great promise, as evidenced by favourable fish growth rates in reservoirs. However, despite concerted efforts by state institutions, actual production consistently falls short of projected targets. This underperformance can be attributed to several systemic challenges, most critically the absence of reliable production statistics and a lack of fundamental data on species richness, abundance indices and population dynamics within these aquatic ecosystems. This knowledge gap has prevented the development of scientifically grounded, specific management plans that are essential for the sustainable development of the sector.

Given that effective management and sustainable exploitation policies must be based on a solid understanding of fish ecobiology, a thorough evaluation of ichthyological communities in Tunisian reservoirs is both necessary and urgent (Mili, 2017; Mili et al., 2021a).

This study is a key part of a collaborative research and development project involving the Higher Institute of Marine Sciences in Bizerte (ISSMB), the General Directorate of Fisheries and Aquaculture (DGPA), the Technical Aquaculture Centre (CTA) and the National Institute of Marine Sciences and Technologies (INSTM). The study's primary objective is to determine the status of fish populations in Tunisian reservoirs. The scientific findings and technical recommendations generated have been formally communicated to policymakers in the fisheries and aquaculture sectors to inform decision-making related to reservoir exploitation.

2. Materials and Methods

A standardised sampling protocol for freshwater fish was developed in collaboration between the ISSMB and the CTA. This protocol utilises multi-mesh gillnets adapted from the European standard CEN 14757 (CEN, 2015). This methodology generates a comprehensive dataset encompassing species richness and the quantitative and qualitative abundance of resources (expressed as number per unit effort (NPUE) and weight per unit effort (WPUE)), as well as population size structure (Laouar, 2019; Mili, 2017; Mili et al., 2016).

Tailored specifically for Tunisian reservoirs, the technique employs both benthic and pelagic multi-mesh nets. These nets are patented nationally, were deployed for the first time in Tunisia by the ISSMB and are made of invisible monofilament. They feature a geometric series of eight mesh sizes ranging from 18 mm to 80 mm, with thread diameters of either 0.23 mm or 0.28 mm. They are assembled at a ratio of 1.25 (Mili et al., 2016; Mili et al., 2022).

The sampling design adhered to CEN (2015) guidelines regarding timing, net quantity, placement and soaking duration. A stratified random sampling approach was implemented to account for the heterogeneous spatial distribution of fish, with sampling effort allocated proportionally to the volume of each depth stratum (0–3 m, 3–6 m, 6–12 m, etc.).

The research encompassed 14 dam reservoirs from 2013 onwards: Sidi Salem, Sidi Saad, Seliana, Bekbeka, Kasseb, Bezirekh, Laabid, Mlaabi, Sidi Barrak, Lahjar, Ghezala, Bir Mcherga, Bouheurtma and Mellegue (Mili, 2017). Seasonal monitoring at the Seliana and Kasseb reservoirs (May 2015–May 2016) was specifically conducted for methodological validation (Laouar, 2019).

3. Key findings

3.1 Taxonomic composition and species richness

Systematic sampling identified eight species of freshwater fish across the surveyed reservoirs: thin-lipped grey mullet (*Chelon ramada*), flathead grey mullet (*Mugil cephalus*), pikeperch (*Sander lucioperca*), common carp (*Cyprinus carpio*), roach (*Rutilus rutilus*), common rudd (*Scardinius erythrophthalmus*), callens minnow (*Pseudophoxinus callensis* Guichenot, 1850) and barbel (*Luciobarbus callensis*). Notably, despite their confirmed presence in some systems, no specimens of catfish (*Silurus glanis*) and European eel (*Anguilla anguilla*) were captured, which highlights potential sampling limitations for these species (Mili, 2017; Mili et al., 2017).

3.2. Spatial Distribution

Analysis revealed a pronounced vertical stratification, with the 0–3 m stratum yielding the highest catch densities (44% of the total). Fish assemblages predominantly occupied the upper water column (below 12 m), with the 0–3 m zone being the most densely populated, and the 0–6 m stratum exhibiting the greatest species diversity. No fish were captured below 20 m, suggesting a biological limit imposed by dissolved oxygen concentrations approaching critical thresholds (5 mg/l) at depths below 6 m (Mili, 2017; Mili et al., 2022; Mili et al., 2021a). Furthermore, horizontal distribution patterns showed the highest fish concentrations in the surface layers of the deepest reservoir zones, near the dam wall. This heterogeneous distribution is consistent with global studies indicating that fish community structure is principally governed by reservoir depth and chlorophyll a concentration (Mehner et al., 2005), as well as a complex set of physicochemical and environmental factors (Mili, 2017).

3.3. Production yields

A significant gradient in productivity was observed among reservoirs. Numerical and biomass yields ranged from a maximum of 446.43 individuals/1000 m² and 28.75 kg/1000 m² at the Lahjar reservoir to a minimum of 6.25 individuals/1000 m² and 0.67 kg/1000 m² at the Mlaabi reservoir (Mili, 2017; Mili et al., 2021a). Reservoirs such as Sidi Barrak, Sidi Salem, Seliana and Sidi Saad were classified as moderately productive (2015). In contrast, Kasseb, Bekbeka, Ghezala, Laabid, Mlaabi and Bouheurtma displayed critically low biomass levels, necessitating immediate intervention to enhance the fish stock. This generally low to moderate productivity is attributed to the recent introduction of many species, ongoing exploitation pressure and insufficient annual mullet fingerling stocking volumes. Benthic nets proved highly effective, capturing 98% of individuals; however, certain morphologically and behaviourally distinct species (eels and catfish) remain undersampled by this method (Mili, 2017).

3.4. Community Structure and Trophic Balance

Functional group analysis revealed a marked trophic imbalance. Cyprinids dominated the catches, accounting for 78% of the total number and 76% of the total weight, compared to just 6% and 8%, respectively, for piscivorous species (Mili, 2017; Mili et al., 2021a). This indicates an ecosystem state skewed towards planktivores and detritivores. The low abundance of detritivorous mullets, which are a key indicator of ecosystem quality, further highlights this imbalance and the critical dependency on stocking programmes. Biodiversity indices confirmed this poor structural state, with low Shannon (H' <1.5) and equitability (E) values reflecting impoverished and uneven communities, which are often dominated by a single cyprinid species (Mili et al., 2021a). However, these metrics are strongly influenced by environmental conditions, necessitating cautious interpretation.

3.5. Population demographics

Size-frequency analyses provided insights into stock status. The populations of carp and mullet were predominantly composed of young individuals, which confirms successful stocking and acclimatisation. However, the scarcity of adults indicates potential overexploitation and requires urgent management intervention (Mili, 2017). The roach and rudd populations exhibited balanced size structures (11–34 cm), indicating stable exploitation levels. Pikeperch stocks were generally low, except in the Seliana reservoir, where a broader size distribution was observed. Barbel populations in the Sidi Barrak, Kasseb and Bir Mcherga reservoirs were found to be in fragile equilibrium (Mili et al., 2017; Mili et al., 2023).

3.6. Biometric relationships

Length-weight relationships were established for the six principal species (*R. rutilus*, *S. erythrophthalmus*, *S. lucioperca*, *C. carpio*, *C. ramada* and *L. callensis*). The parameters (a) and (b) ranged from 0.0016 to 0.1774 and from 2.859 to 3.260, respectively, and were strongly correlated (R^2: 0.868–0.994) (Mili, 2017; Mili et al., 2017). Most populations (barbel, carp, roach and pikeperch) exhibited negative allometric growth ($b < 3$). Thin-lipped mullet generally showed negative allometry, except in Seliana and Sidi Barrak, where positive growth ($b > 3$) was observed. The Rudd population from the Laabid reservoir was the only one with clear positive allometry. Statistical analyses confirmed significant inter-reservoir variability in length-weight relationships for all species except carp.

3.7 Spatio-temporal dynamics: Case studies of the Seliana and Kasseb reservoirs

3.7.1. Seliana

Seasonal sampling confirmed that spring was the optimal survey period due to peak fish mobility and productivity (Mili, 2017; Laouar, 2019). The community was dominated by thin-lipped mullet and rudd. The species exhibited distinct spatial niches: roach and rudd were concentrated near the centre of the reservoir, while mullet aggregated in deep waters near the dam. Pikeperch distributed themselves according to their prey: barbel were found downstream, and roach and rudd in the middle of the water column. Mullet yields increased in spring (0–3 m: 50–482 individuals/1000 m^2; 3–6 m: 83–282 individuals/1000 m^2), which was influenced by oxygen levels and diet (Chargui et al., 2021). Forage fish (roach and rudd) exhibited high abundance (CPUE: 150–300 ind./1000 m^2 in 0–3 m), as well as winter migrations to shallow spawning grounds. Pikeperch yields were highest in autumn (0–3 m: 100–249 ind./1000 m^2) but plummeted in spring during spawning, which was characterised by reduced mobility and vulnerability to fishing gear (Toujani et al., 2000). Barbel concentrations were highest at river inflows (0–66 ind./1000 m²) and showed no seasonal variation (Laouar, 2019; Chargui et al., 2021).

3.7.2. Kasseb

Fish resources were more uniformly distributed. The community was characterised by high barbel abundance and a low occurrence of its predator, the pikeperch, alongside moderate concentrations of mullet in deep areas (Mili, 2017; Laouar, 2019). The absence of pikeperch and the presence of non-reproductive mullet during the traditional closed season (March–April) led to a recommendation to revise the fishing calendar, intending to improve operator incomes without compromising fish stocks. Barbel were highly concentrated at river inflows (0–16 individuals per 1000 m²), and their decline was linked to introduced predators and low fecundity (Kraiem, 1994; Mili et al., 2017). Mullet only appeared in spring at low densities (less than 24 individuals per 1000 m²), representing juveniles that were stocked in 2015 and were migrating from release points to deep, oxygen-rich feeding grounds (Mili et al., 2023; Ben Rejeb-Jenhani et al., 2019). This supports the proposal to adjust the closed season to align with peak mullet availability.

4. Conclusion

This comprehensive assessment reveals that Tunisian reservoirs are generally characterised by low to moderate productivity and biodiversity, as well as significant trophic imbalances that often favour cyprinid dominance. Key constraints include reliance on stocking certain species, insufficient sampling of specific ecological groups and exploitation pressures leading to stunted population structures for some species. The spatial and temporal dynamics documented, particularly in Seliana and Kasseb, provide a scientific basis for refining management practices, including optimised sampling windows and revised fishing seasons. The findings emphasise the need to transition from opportunistic exploitation to science-based management, incorporating targeted stocking, strict regulations, and ongoing monitoring to promote the sustainable development of this promising sector.

III. Population dynamics of freshwater fish species

1. Research context and objectives

The significant growth rates observed in species introduced to Tunisian reservoirs, combined with tangible production outputs, highlight the considerable potential of these aquatic systems and the need for further development and optimisation. Historical operational data from various freshwater fisheries indicate that fish stocks are vulnerable to overexploitation (Mili, 2017; Laouar, 2019). Consequently, a comprehensive understanding of species biology is fundamental to implementing effective and sustainable resource management strategies.

The accurate definition of the parameters that govern the reproductive strategies of exploited species is a prerequisite for science-based management. Critical biological data, including size at first sexual maturity, sex ratios, absolute and relative fecundity, and spawning periodicity, constitute essential inputs for stock assessment models. These enable the precise identification of stock components and the reliable estimation of spawning stock biomass. Beyond predicting population fluctuations, ichthyological community studies provide crucial insights into environmental influences and intra-population dynamics, including species interactions and predator–prey relationships (Chargui et al., 2025).

The scarcity of high-resolution quantitative and qualitative data on fish population dynamics across Tunisian reservoirs, with the notable exception of Sidi Salem, provided the primary impetus for this investigation. The immediate research objectives focus on defining key exploitation parameters (optimal capture size and mortality rates) for dominant populations by integrating biological data (age structure, growth rates and age at maturity). The long-term goal is to establish a framework for the rational and sustainable management of Tunisia's freshwater fish resources, thereby enhancing the productivity and economic viability of its inland aquaculture sector.

2. Materials and Methods

Due to the ecological and economic importance of mullet species in Tunisian reservoir fisheries, the initial research focused on the population dynamics of *M. cephalus* and *C. ramada* in five representative reservoirs (Joumine, Bir Mchergua, Kasseb, Seliana and Sidi Barrak). Subsequently, the scope of the investigation was broadened to include the dominant species in the Kasseb and Seliana reservoirs: the rudd (*S. erythrophthalmus*), the pikeperch (*S. lucioperca*) and the barbel (*L. callensis*).

The temporal sampling design involved the seasonal collection of mullet specimens from the Joumine, Bir Mchergua and Sidi Barrak reservoirs in 2011. This was followed by the comprehensive monitoring of the dominant species in the Seliana and Kasseb reservoirs from May 2015 to May 2016 (Mili et al., 2015b; Mili et al., 2022). Age determination and growth analysis employed scale reading (scalimetry) techniques, with data processing conducted using the FISAT II software package developed by the FAO. Linear growth in length and weight was modelled using the Von Bertalanffy growth function (VBGF), while the relationship between somatic growth and scale radius was used for back-calculation of fish lengths. VBGF parameters (L_∞, k, t_0) were estimated using multiple routines within FISAT II (Elefan I, Shepherd and Powell-Wetherall methods), and model selection was based on growth performance indices (Mili et al., 2022).

Additional analyses revealed the relationships between the relative growth of morphometric measurements (total length Lt, fork length Lf and standard length Lst) and weight-length parameters for the main species across 14 reservoirs (Mili et al., 2015b). Analysis of covariance (ANCOVA) was used to test for significant variability in growth rates among populations.

The mortality analysis focused on estimating the rates of fishing (F), natural (M) and total (Z) mortality through size-based methods and cohort analysis for the dominant populations (rudd, thin-lipped mullet and pikeperch in Seliana; thin-lipped mullet and barbel in Kasseb) in the reservoirs, using FISAT II algorithms. These analyses also provided estimates of the optimal capture size and recruitment parameters (Mili et al., 2022).

The assessment of reproductive strategy involved determining size at first maturity (Lm50), fecundity, reproductive seasonality, and spawning characteristics to quantify reproductive capacity. For common carp (*C. carpio*) in the Sidi Saad reservoir, these parameters were derived through monthly sampling over two years. Macroscopic gonad staging, coupled with gonadosomatic index (GSI) analysis, enabled the precise determination of maturation stages and reproductive timing (Mili, 2017).

3. Key findings

3.1. Mullet population dynamics (*M. cephalus* and *C. ramada*)

Highly significant correlations ($R^2 > 0.98$) were observed among all three length measurements (TL, FL and SL). *M. cephalus* exhibited negative allometric growth patterns across most length relationships, except for positive allometry between TL and SL in Joumine reservoir. *C. ramada* demonstrated similar allometric patterns, with isometric growth between TL and FL. Scalimetric analysis identified ten age classes for *C. ramada* and eight for *M. cephalus* in the Bir Mchergua and Joumine reservoirs (Mili et al., 2015b). Asymptotic length ($L\infty$) values ranged from 51.4 cm to 65.2 cm for *M. cephalus* in Bir Mchergua and Joumine, respectively, while *C. ramada* attained $L\infty$ values of 58.5 cm (Sidi Barrak), 57.0 cm (Seliana) and 48.6 cm (Kasseb) (Mili et al., 2023). Asymptotic weight values for thin-lipped mullet in the Sidi Barrak reservoir were intermediate between the Joumine and Bir Mchergua populations (Mili, 2017). Comparative analysis revealed no significant differences between the age estimation methods used (scalimetry and length-frequency analysis). An interspecific comparison showed that *M. cephalus* exhibited significantly faster linear and weight growth rates across all five reservoirs (Mili et al., 2015b; Mili et al., 2022), with the Joumine reservoir providing the most favourable ecological conditions for mullet growth.

The optimal capture sizes for the mullet populations were found to be 37.62 cm (Seliana) and 31.42 cm (Kasseb), with the corresponding recruitment sizes being 18.0 cm and 19.6 cm, respectively (Mili, 2017; Mili et al., 2023). Mortality analysis revealed size-specific patterns: fishing mortality (F) disproportionately affected larger size classes, while natural mortality (M) primarily impacted juveniles (ages 1–2).

Virtual Population Analysis (VPA), which integrates all dynamic parameters, indicates that mullet stocks in both the Seliana and Kasseb reservoirs are currently being exploited at levels approaching the maximum sustainable yield (Mili et al., 2015b; Mili, 2017). This exploitation status necessitates the implementation of regular population monitoring, enhanced fingerling stocking programmes and a strategic reduction in fishing effort.

3.2. *L. callensis* dynamics

Scale-based ageing identified five distinct age classes (I+ to V+) in populations at Kasseb. The population was dominated by two- and three-year-old individuals (mean lengths: 29.3 cm and 37.32 cm, respectively). Consistent VBGF parameters ($L\infty$, k) were obtained using multiple estimation methods, with high agreement in performance indices. The optimal capture size for maximum yield per recruit was calculated to be 38.4 cm. Mortality rates were estimated at M = 0.45, F = 0.73 and Z = 1.18. Natural mortality predominantly affected juveniles (21–27 cm), while fishing mortality targeted larger, older individuals (4+ years, 29–43 cm) (Mili et al., 2015b; Mili et al., 2022; Mili, 2017). Current exploitation levels approach maximum economic yield, indicating near-optimal management of barbel stocks in Kasseb reservoir.

3.3. *S. lucioperca* population parameters

Pikeperch populations in Seliana exhibited a broad size distribution (8.5–53.5 cm) across sampling periods. VBGF parameters indicated asymptotic length ($L\infty$) and weight ($W\infty$) values of 58.4 cm and 1674.38 g, respectively. Mortality estimates were M = 0.48, F = 0.99 and Z = 1.47, with an optimal capture size of 38.51 cm. The calculated exploitation rate for maximum sustainable yield (MSY) was 0.672, which slightly exceeded the current level of 0.564 (Mili, 2017; Laouar, 2019). This warrants continued monitoring and a potential reduction in fishing permits to ensure stock recovery.

3.4 *S. erythrophthalmus* demographics

Rudd populations in Seliana comprised four age classes (0+ to III+), ranging in size from 11 to 31 cm. Growth parameters indicated $W\infty = 318.6$ g and $L\infty = 32.1$ cm, with mortality rates of M = 0.693, F = 0.78 and Z = 1.47. VPA analysis revealed significant natural mortality among juveniles, while fishing mortality targeted older individuals (two to three years old, 15–30 cm). As the average capture size (25.85 cm) exceeds the optimal length (21.4 cm), and the current exploitation rate (0.407) is approaching Emax, it is essential to continuously monitor the population to maintain a balanced forage fish community (Mili, 2017; Laouar, 2019).

3.5 Reproductive biology of *C. carpio*

Investigations into carp populations in Sidi Saad Reservoir revealed female-biased sex ratios throughout the sampling period. The size at first maturity was found to be 15.8 cm for males and 22.5 cm for females. Macroscopic analysis identified six distinct gonad developmental stages, enabling the reproductive cycle to be characterised in detail (Hajlaoui et al., 2019). Integrated gonadosomatic index (GSI) and histological analysis revealed three primary reproductive phases: maturation (September–March), spawning (March–July) and sexual rest/recovery (July–September). Analysis of oocyte development confirmed a serial spawning strategy in this population (Hajlaoui et al., 2016).

IV. Ecotoxicological assessment of freshwater fish species

1. Context and objectives

A strategic analysis of Tunisia's fisheries and aquaculture sector has revealed an urgent need to increase the commercial value of domestic freshwater fish production. This can be achieved through two primary channels: (1) targeted promotion in local markets to stimulate consumer demand and increase market value; and (2) development of export opportunities for fresh, frozen and processed value-added products in international markets where there is established demand. The underutilisation of Tunisia's freshwater fish resources stems primarily from a lack of data on their chemical safety profile and nutritional quality (Mili, 2017; Laouar, 2019).

Furthermore, reservoirs are increasingly subject to chemical contamination from agricultural runoff, which creates potential pathways for the bioaccumulation of hazardous substances in aquatic organisms. This environmental pressure necessitates the systematic monitoring of reservoir ecosystems and their biological communities (Ennouri et al., 2017).

In order to address these knowledge gaps and support sector development, the present study was designed to quantitatively assess essential micronutrients (calcium, magnesium, iron and zinc) and toxic heavy metals (cadmium, lead and mercury) in the muscle tissue of commercially important freshwater fish species that are popular with Tunisian consumers.

2. Materials and methods

The study focused on the thin-lipped grey mullet (*Chelon ramada*), which was sampled as the predominant species from the Sidi Salem and Sidi Saad reservoirs. For the Bezirk and Lahjar reservoirs, the assessment included both *C. ramada* and *S. lucioperca*, enabling a comparative analysis (Ennouri et al., 2017). A comprehensive sampling protocol was implemented with monthly collections conducted throughout 2013 to account for potential seasonal variations.

Advanced analytical techniques were employed for precise quantification: Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS) was used to detect Cd and Pb, providing the required sensitivity for trace metal analysis. Mercury concentrations were determined using a dedicated direct mercury analyser. Essential elements (Zn, Fe, Mg and Ca) were quantified using flame atomic absorption spectrophotometry (FAAS) (Ennouri et al., 2017; Mili, 2017). All analytical procedures followed strict quality assurance and quality control protocols, including method blanks, duplicates and certified reference materials, to ensure data reliability.

3. Key findings

3.1. Toxic Metal Contamination Assessment

Analysis of Cd, Pb and Hg concentrations in *C. ramada* muscle tissue revealed spatial variation across the four reservoirs. The highest contamination levels were recorded in specimens from Lahjar and Bezirik, with maximum values of approximately 0.04 µg/g of wet weight for both cadmium (Cd) and lead (Pb), and 0.08

μg/g of wet weight for mercury (Hg). Statistical analysis confirmed that these concentrations were significantly higher than those measured in mullet from the Sidi Salem and Sidi Saad reservoirs (Ennouri et al., 2017).

Notably, all measured concentrations remained below the maximum permissible limits established by the Tunisian Ministry of Agriculture (2015 revision), indicating compliance with national food safety regulations (Mili, 2017).

Similar patterns were observed in pikeperch specimens from the Lahjar and Bezirik reservoirs, with the highest metal concentrations found in fish from Bezirik: 0.04 μg/g ww (Cd), 0.2 μg/g ww (Pb) and 0.1 μg/g ww (Hg) (Ennouri et al., 2017). While these values also remained within regulatory limits, statistical analysis revealed significant differences between reservoirs for Pb and Hg concentrations, but not for Cd (Mili, 2017). This spatial variation suggests localised differences in contamination sources or environmental processes affecting metal bioavailability.

3.2. Essential micronutrient profile

Analysis of essential elements (Zn, Fe, Mg and Ca) in *C. ramada* muscle tissue demonstrated remarkable consistency across the four reservoirs, with no statistically significant differences in mean concentrations (Ennouri et al., 2017). The mean concentrations (μg g^{-1} wet weight ± standard error) were quantified as follows: Zinc

(14.4 ± 0.8), iron (32.3 ± 1.2), magnesium (66 ± 5) and calcium (89 ± 2) (Mili, 2017).

The observed zinc levels reflect the complex interplay of multiple factors influencing metal accumulation dynamics, including direct exposure pathways (aqueous absorption) and trophic transfer (dietary intake). Abiotic parameters, particularly physicochemical water characteristics, significantly affect metal bioavailability and uptake (Ennouri et al., 2017). The correlation between Zn concentrations and trophic position lends weight to the hypothesis that dietary intake is the primary exposure route for this essential element.

This comprehensive assessment allows us to conclude that the Sidi Salem, Sidi Saad, Bezirik and Lahjar reservoirs are unaffected by significant metallic contamination. Consequently, consuming fish from these ecosystems poses no identifiable health risks, as all toxic element concentrations remain below regulatory thresholds.

In addition to ensuring food safety, this study provides valuable baseline data on the micronutrient composition of two commercially important fish species in Tunisian reservoirs. This database will serve as a scientific reference for future monitoring and as a foundation for developing targeted management strategies for ecosystem restoration and human health protection.

V. Synthesis and Concluding Remarks

A comprehensive diagnostic assessment of Tunisia's inland aquaculture sector reveals significant potential for socio-economic development through improved production systems. The sector can generate significant employment opportunities for rural communities adjacent to reservoirs and contribute to national food security by providing valuable sources of animal protein.

However, realising this potential requires the implementation of robust management frameworks, including the regular monitoring of exploitation levels and the systematic control of fishing effort, to ensure the sustainable utilisation of fish resources. While the current assessment indicates that most fish populations exist at optimal exploitation levels, stock densities remain suboptimal and would benefit from strategic enhancement programmes involving the transfer of broodstock and the supplemental stocking of fingerlings.

Ecobiological investigations confirm that introduced species have successfully adapted to local conditions, demonstrating favourable growth and development patterns in reservoir environments.

Crucially, the ecotoxicological evaluation provides scientific evidence that fish from the Sidi Salem, Sidi Saad, Bezirik and Lahjar reservoirs are free from hazardous metal contamination. All measured concentrations of toxic elements were substantially below national and international safety standards, confirming that these products are safe for human consumption and suitable for domestic and international markets.

Section 2: Development of aquaculture and exploitation of fish resources in reservoirs

I. Optimisation of stocking and fish collection techniques

1. Forage fish management

1.1. Research context and objectives

Since 2013, ecological studies have consistently demonstrated inadequate abundances of forage fish species in Tunisian reservoirs. This deficiency in cyprinid populations creates significant trophic imbalances within aquatic ecosystems, particularly in reservoirs with high densities of predatory fish such as pikeperch (*S. lucioperca*) and catfish, relative to their primary prey, roach (*R. rutilus*) and rudd (*S. erythrophthalmus*) (Mili, 2017; Mili et al., 2017; Laouar, 2019).

The historical introduction of roach by the National Fisheries Office in the 1960s, followed by the intentional introduction of common rudd under the Tunisian-German GTZ cooperation project for predator forage purposes, specifically established these species as fundamental components of reservoir ecosystems (Mili et al., 2017). This research programme was designed to address critical gaps in forage fish availability by developing optimised protocols for broodstock collection, transfer and stocking operations. The ultimate objective is to establish sustainable predator–prey equilibria to enhance overall reservoir productivity and exploitation efficiency.

1.2 Materials and Methods

The research programme adopted a systematic approach, beginning with the design and construction of specialised collection equipment targeting roach and rudd broodstock. Field operations were conducted at the Bezirekh reservoir in 2012 and the Sidi Salem reservoir in 2014 and 2016, evaluating four distinct mesh sizes (18, 22, 24 and 26 mm) in accordance with standardised net construction protocols specific to Tunisian reservoir conditions (Mili et al., 2017).

Complementary infrastructure included specialised holding cages with a volume of 2 m^3, constructed from galvanised steel and 16 mm mesh netting. This enabled weekly health assessments prior to translocation. Transport was via oxygenated 1 m^3 tanks mounted on utility vehicles. Analytical methods incorporated principal component analysis (PCA) to evaluate mesh performance differentials, while selectivity parameters (selection range, SR; selectivity factor, SF) were calculated to determine gear efficiency. Additional biometric analyses focused on reproductive parameters (size at maturity, gonadosomatic index and sex ratios) to validate the temporal optimisation of collection operations (Mili, 2017; Mili et al., 2017).

1.3. Key findings

- **Gear performance and selectivity**

Seventy-one collection operations conducted during the February–March period from 2012 to 2016 yielded 8,901 specimens. Of these, 6,375 were successfully transferred to recipient reservoirs, including Sidi Barrak, Joumine, Ghezala and Mellegue, among others (Mili et al., 2021a). Stocking densities were calibrated according to reservoir carrying capacity metrics (Mili, 2017; Mili et al., 2017).

A mesh efficiency analysis demonstrated the superior performance of the 22–24 mm configuration, which achieved an optimal balance between capture efficiency (57–62% of the total catch) and mortality rates (less than 8%). The 18 mm mesh resulted in excessive mortality (over 25%) due to tissue damage caused by entanglement, while the 26 mm mesh had inadequate capture rates despite low mortality (Mili, 2017; Mili et al., 2017). Selectivity coefficients confirmed these findings (SR = 1.1 for 22–24 mm; SR = 1.35 for 18 mm), establishing medium mesh sizes as the optimal choice for selective broodstock harvesting (Mili et al., 2021a).

- **Health status and reproductive condition**

Pathological screening revealed minimal parasitisation (2–4% prevalence) by *Ligula intestinalis* (Mili, 2017; Mili et al., 2017). Reproductive assessments indicated male-biased sex ratios (52–57%) and advanced maturation stages during the February–March collections. More than 97% of the captured specimens exceeded the size at maturity thresholds (11.9 cm for roach and 12.0 cm for rudd). Gonadosomatic indices confirmed reproductive readiness (female GSI: 1–18%; male GSI: 0.5–17%) (Mili, 2017; Mili et al., 2017).

Post-stocking validation through multi-mesh gillnet surveys confirmed the successful establishment of the fish in six recipient reservoirs, demonstrating the efficacy of the protocols developed to enhance the availability of forage fish and the trophic balance.

2. Mullet fry production and management

2.1. Operational Challenges

Mullet stocking is fundamental to Tunisian inland aquaculture, with an annual production target of 9 million fry to be stocked across 25 major reservoirs and hill lakes (Mili, 2017; Mili et al., 2021a; Mili et al., 2023). Critical constraints include: (1) species misidentification due to morphological similarities and depigmentation variants among Mugilidae fry; (2) suboptimal harvest timing relative to natural abundance cycles; and (3) the technical limitations of existing Italian-style seine nets.

This research addressed these challenges by focusing on three areas: (1) molecular identification protocols, (2) spatiotemporal abundance mapping, and (3) improvements to the design of collection gear and acclimatisation protocols (Mili et al., 2013).

2.2. Methodology and analytical framework

Field collections were carried out in major northern hydrological systems (Oued Medjerda, Raoued and Maftouh El Makki) and used cytochrome b sequencing to genetically authenticate *C. ramada*, *C. aurata* and depigmented variants. Principal component analysis was used to delineate spatiotemporal abundance patterns, while redesigned seine nets (as detailed in Mili et al., 2013) were evaluated against traditional gear. Acclimatisation protocols involved reducing salinity progressively to 2‰ over 72 hours, with comprehensive monitoring of physiological responses and survival rates (Mili, 2017).

2.3. Key findings

- **Species Distribution and Harvest Planning**

Genetic analyses resolved historical identification uncertainties, confirming distinct cytochrome b signatures for the target species. Spatiotemporal mapping revealed pronounced seasonal successions: *M. cephalus* abundance peaks in September, *C. aurata* dominates in October, and *C. ramada* is prevalent from February to April, as observed across monitoring stations (Mili et al., 2013). These findings enabled precise harvest scheduling: September–December (*M. cephalus*), January–March (*C. aurata*) and February–April (*C. ramada*).

- **Gear performance and acclimatisation**

The redesigned seine demonstrated significantly improved pursing efficiency and capture volumes compared to traditional gear. However, acclimatisation in hatcheries revealed a critical vulnerability to fungal pathogens (60% mortality), in contrast to minimal mortality related to osmotic shock (Mili, 2017). This finding necessitated revised protocols recommending direct stocking without intermediate holding periods to avoid pathogen proliferation in confined systems.

3. Chinese carp broodstock collection

3.1 Context and objectives

The artificial propagation of the Chinese carp species (grass carp, silver carp and bighead carp) requires the collection of broodstock from reservoir populations each year. Increasing fishing pressure and the vulnerability of the fish to injury when caught in conventional gill/trammel nets have led to the development of specialised collection methodologies to ensure viable gamete production for hatchery operations (Mili, 2017; Mili et al., 2021b).

3.2. Engineering solutions

A non-purse seine design featuring reinforced wings, optimised cod end geometry, and controlled retrieval mechanisms was engineered to minimise specimen stress and physical damage (Mili, 2017). Four operational trials demonstrated the effective capture of 52 Chinese carp (41–83 cm) and 63 common carp (mean 52 cm), with zero collateral damage and 100% survival during transfer operations (Mili, 2017; Mili et al., 2021b).

3.3. Conclusions

The integrated research programme delivered the following: (1) validated selective collection protocols for forage fish enhancement, (2) genetic identification tools and abundance models for mullet fry management, and (3) engineered solutions for sustainable broodstock collection. Ongoing development focuses on mechanised purse seining systems to improve the efficiency and scale of operations for sustaining Tunisia's inland aquaculture production.

II. Advanced techniques for exploiting and propagating freshwater fish resources

1. Controlled reproduction of pikeperch (*S. lucioperca*) in cage systems

1.1. Research context and objectives

Pikeperch is a particularly valuable species in Tunisian reservoir fisheries due to its rapid growth characteristics and superior flesh quality, demonstrating significant commercial potential. Despite its successful introduction to 29 waterbodies (16 dam reservoirs and 13 hill lakes), the species remains substantially underutilised relative to its ecological and economic potential (Mili, 2017). National production figures reflect this, with recorded yields of 212 tonnes in 2014 and 140 tonnes in 2022, the majority of which (83%) came from the Sidi Salem reservoir (DGPA, 2015; DGPA, 2022).

Traditional enhancement strategies have relied on stocking fry produced in hatcheries and transferring broodstock to deficient systems. However, these approaches present significant economic and logistical constraints (Laouar et al., 2016). This research programme has therefore established a novel investigation into the in situ hormonal induction of spawning in cage systems, to develop a more efficient and cost-effective propagation methodology.

1.2. Materials and Methods

A comprehensive reproductive physiology study was conducted during the 2013 and 2015 spawning seasons. Broodstock were collected using gillnets in the Sidi Salem and Nebhana reservoirs. Specimens were handled carefully to minimise stress and were treated with physiological saline (NaCl 0.9%) or hydrogen peroxide solutions to treat fungal infections. Sex determination and maturation staging were performed using biopsies before hormonal intervention.

The experimental design incorporated cages measuring 1 m^3 and 2 m^3, with a galvanised steel frame and 20 mm mesh, which were deployed in the Sidi Salem, Sidi Saad and Lahma reservoirs (Mili et al., 2021). Artificial nesting substrates (wooden frames covered with artificial grass mats) were provided. Hormonal induction involved the use of HCG at a dose of 400 IU/kg, administered either intramuscularly or intraperitoneally, either as a single dose or divided into multiple doses. Control groups were maintained at the Boumhel pilot station. Following spawning, the eggs were transferred for incubation or maintained in situ for developmental studies.

Oocyte diameter, absolute fecundity (estimated from pre- and post-spawning weight differences) and relative fecundity were quantified using micrometric and gravimetric analyses (Laouar et al., 2016; Mili, 2017).

1.3. Key Findings

- **Gonadal development and maturation dynamics**

Histological examination revealed three distinct oocyte developmental stages: Stage 1 (60% prevalence), characterised by a central germinal vesicle (GV) position and numerous lipid droplets; Stage 2 (30%), showing peripheral GV migration and fewer, larger lipid inclusions; and Stage 3 (10%), exhibiting complete GV migration and lipid droplet fusion (Mili, 2017).

- **Hormonal response and spawning kinetics**

Water temperatures during trials ranged from 12.5 to 15.0 °C. The mean latency period between hormonal stimulation and ovulation was 96 ± 30 hours. Intraperitoneal administration yielded significantly shorter response times (84 ± 17 hours) than intramuscular delivery (99 ± 32 hours) (Laouar et al., 2016). Statistical analysis confirmed that the injection protocol ($p = 0.47$), the number of doses ($p = 0.64$) and the sex ratio ($p = 0.33$) did not significantly affect latency duration. Spawning occurred within 3–5 days (Stage 1 oocytes), 3–7 days (Stage 2) and 3 days (Stage 3) post-stimulation (Mili, 2017).

- **Reproductive performance metrics**

Spawn weight ranged from 50 to 686 g (female weight: 645 to 3,500 g), representing 3.12% to 21.41% of somatic weight. The relationship between egg mass (WEG) and female weight (W) was as follows: WEG = 0.185W - 81.42. The mean absolute fecundity was 327,860 eggs per female (range: 69,156–857,500), equating to a relative fecundity of 203,891 eggs per kg. The fecundity-weight relationship was described as follows: FA = 209.7W - 23,139 (Mili, 2017).

- **Incubation parameters**

Under natural reservoir temperatures (13.2–16.8 °C), incubation required 50.49–111.3 degree-days (3–7 days). These results were consistent with the models of Lappalainen et al. (2003) ($p = 0.957$ hours; $p = 0.917$ degree-days). The mean egg diameter was 1.267 mm (range: 0.997–1.439 mm). Larval production was 12,985–30,508 per female, with hatching rates of 1.75–21.18%. Optimal development occurred at 59.2 degree-days (Mili, 2017).

This research conclusively demonstrates the technical feasibility of pikeperch propagation in situ via hormonal induction in cage systems. A single intramuscular/intraperitoneal injection of 400 IU/kg HCG at a 1:1 sex ratio proved sufficient for spawning induction (Laouar et al., 2016). Future refinements should focus on broodstock health management to improve spawn quality and consistency.

2. Innovation in Nile tilapia (*O. niloticus*) culture systems

2.1. Research context and objectives

Despite its recognised potential for production intensification, cage aquaculture in Tunisian reservoirs remains primarily experimental. The development of Nile tilapia culture specifically requires engineered solutions that address the following: (1) biofouling resistance, (2) waste management and (3) structural stability in reservoir environments. Preliminary trials (2010–12) in the Lahma and Ghezala reservoirs using conventional designs revealed these limitations, leading to the development of specialised cage systems (Mili et al., 2021).

2.2 Materials and Methods

Four experimental cages with a volume of 50 m^3 (5×5×2.5 m) featuring square mesh configurations of 12 mm and 20 mm were constructed to optimise water exchange and reduce fouling compared to traditional diamond mesh. The net panels were mounted on reinforced polyamide headropes (Ø = 10 mm) and weighted with 6 kg lead core lines to ensure structural integrity. Anti-fouling treatment through net dyeing was implemented to enhance durability and reduce stress on stocked fish (Mili, 2017; Mili et al., 2021).

2.3. Performance evaluation

The engineered cage systems demonstrated significant improvements over conventional designs.

- The square mesh configuration prevented clogging and maintained >90% water exchange efficiency.
- Enhanced waste removal through improved flow dynamics
- They facilitated natural recruitment through the selective escapement of fry while retaining market-size fish.
- They withstood meteorological stressors, including wind-induced waves and currents.

Despite the limited duration of the trials (two years), these technological innovations proved to be robust and economically viable for small-scale operators. The design allows for: (1) high stocking densities, (2) simplified maintenance, and (3) integration with natural reproduction cycles through controlled fry escapement (Mili et al., 2021). These findings provide a technical foundation for the commercialisation of tilapia cage culture in Tunisian reservoirs, addressing production needs and ecological sustainability concerns.

III. Advanced Gear Technology for Optimised Fish Collection in Freshwater Reservoirs

1. Development and implementation of multi-mesh combined nets

1.1. Research context and objectives

This investigation addresses the limitations of current fishing practices in Tunisian reservoir aquaculture. The predominant use of monofilament gillnets poses significant operational challenges due to their inability to be repaired when damaged and their high visibility to fish populations. Technological stagnation in fishing gear, coupled with operators' limited technical capacity for fabrication and manipulation, has substantially reduced productivity and economic returns (Mili, 2017; Mili et al., 2015a). This research initiative has therefore developed and evaluated innovative multi-filament combined net systems to address these systemic challenges.

1.2. Materials and Methods

The engineering programme designed and constructed 25 specialized net units incorporating five distinct mesh configurations (mesh sizes of 40, 50, 55, 60 and 70 mm) using high-density polyamide filament (13,000 m/kg). Detailed technical specifications for the 40 mm mesh configuration can be found in

Mili (2017). Rigorous field testing was conducted in the Ghezala and Seliana reservoir systems in 2010 using standardised sampling protocols to evaluate comparative performance (Mili et al., 2016).

1.3. Performance evaluation

Experimental trials demonstrated significant improvements in capture efficiency and species selectivity.

- Ghezala Reservoir: Large-mesh configurations (55–70 mm) selectively targeted valuable species, including barbel (*L. callensis*) and thin-lipped grey mullet (*C. ramada*), yielding 90 kg and 176 kg, respectively. This represented a 350–400% increase compared to the yields achieved by traditional operators using conventional gear under identical conditions (Mili et al., 2016).
- Seliana Reservoir: The multi-mesh system demonstrated exceptional adaptability, capturing mullet and carp of all sizes, while the 40 mm mesh was specifically optimised for harvesting roach. Notably, the system successfully captured large eel specimens measuring 70 cm, demonstrating its effectiveness in capturing typically elusive species.

Captured specimens consistently exceeded the regulatory size limits, confirming the selective harvesting capacity of the engineered systems. Mullet averaged 47 cm, with exceptional specimens reaching 70 cm.

The superiority of multifilament nets is evident through their enhanced environmental camouflage, full water column coverage and repairability, addressing the critical limitations of conventional monofilament nets (Mili, 2017). Implementation recommendations prioritise these advanced systems for sustainable reservoir management.

2. Optimisation of Gillnet Configurations

2.1 Research context and objectives

The suboptimal performance of reservoir fisheries was directly linked to technical deficiencies in net construction and maintenance practices. A comprehensive sector analysis revealed that inadequate knowledge of gear and improper net rigging were generating substantial operational inefficiencies and economic losses for producers (Mili, 2017; Mili et al., 2015a). This programme implemented a dual intervention strategy, combining technological improvements with comprehensive capacity building.

2.2. Methodology and Implementation Framework

A structured training programme was delivered to operators across five key reservoirs (Sidi Saad, Sidi Barrak, Sidi Salem, Bezirekh and Lahjar). The intervention included:

- Distribution of 240 nets (three nets per operator: one pre-rigged and two raw material sets).

- Hands-on training in advanced net rigging techniques

- Development of Arabic-language technical manuals for sustainable knowledge transfer.

Field validation was conducted through controlled fishing trials at the Sidi Salem reservoir in 2014 to quantify performance improvements (Mili, 2017).

2.3. Technical and socio-economic outcomes

The programme achieved significant advancements in both fishing efficiency and sustainable practices.

- Biodiversity monitoring: Captures of five ecologically and commercially important species were documented: pikeperch (28%), carp (17%), mullet (7%), eel (1%) and forage fish (47%).
- Selectivity optimisation: Mesh-specific selectivity parameters were quantified: 40 mm (SR = 2.1), 55 mm (SR = 1.8) and 70 mm (highest interspecific/intraspecific selectivity).
- Regulatory compliance: All captured specimens exceeded minimum size regulations, demonstrating effective size-selective harvesting.
- Economic impact: The 40 mm mesh configuration demonstrated superior efficiency for harvesting multiple species in the Sidi

Salem reservoir.

Integrating technical training with technology transfer proved highly effective, enabling operators to independently maintain and optimise their gear systems, a critical factor for long-term sustainability (Mili, 2017).

Conclusion and Strategic Perspectives

The experimental results conclusively demonstrate that the sustainable development of Tunisian aquaculture in reservoirs requires integrated technological and management interventions. Key success factors include: (1) advanced stocking protocols for mullet fry, carnivorous species, and forage species; (2) the adoption of engineered fishing systems; and (3) the professionalisation of operator technical capabilities. Cage culture systems present complementary opportunities for intensifying production.

Research perspectives and development framework

Our findings establish five priority areas for future research and development:

Ecosystem Dynamics and Monitoring:

- Enhanced understanding of reservoir ecosystems and fish population dynamics;

- Development of predictive models for ecosystem responses to management interventions

- Implementation of advanced monitoring methodologies

Stocking optimisation

- Evaluation of mullet fry stocking efficiency through mark-recapture studies.

- Designing specialised acclimatisation units to maximise survival rates.

- Development of species-specific release protocols.

Fisheries Management:

- Implementation of CEN 14757 standards for biomass and density estimation.

- Integration of multi-mesh netting with hydroacoustic and electrofishing techniques.

- Investigating spatial, seasonal and diel distribution patterns.

Technological innovation:

- Development of alternative capture systems (longlines and fixed installations).

- Technical optimisation of gear specifications and deployment protocols.

- Impact assessment of novel species introductions (crayfish).

Value chain development:

- Implementation of advanced processing techniques (smoking, filleting and surimi production).

- The extraction and commercialisation of high-value compounds (proteins and polyunsaturated fatty acids).

- Market development for underutilised species (catfish, carp and pikeperch).

Production system optimisation

- Identification of suitable zones for intensive and semi-intensive culture.

- Development of enclosed tilapia production systems in reservoirs and hill lakes.

- Economic modelling to enhance the profitability of freshwater aquaculture.

This framework provides a scientific basis for the sustainable development of Tunisian reservoir aquaculture by integrating ecological, technological and socio-economic factors to maximise productivity while ensuring environmental sustainability.

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