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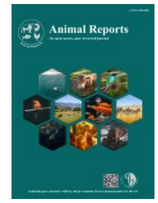

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# Challenges and innovative solutions in sustainable aquaculture: How can it contribute to food security and environmental protection

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**Abstract:** Sustainable aquaculture presents a dual opportunity to meet the nutritional needs of a growing population while alleviating pressure on fragile marine ecosystems. However, realizing this potential requires navigating significant challenges, including pollution, environmental degradation, disease management, resource efficiency, and lack of regulations. In addition, these challenges will be maximized with the need to expand aquaculture by nearly 50% by 2030 to meet increasing global protein needs. Therefore, careful management must be implemented to reduce the potential environmental risk. There are several innovative solutions that could drive sustainable aquaculture growth, including integrated aquaculture systems that can foster efficiency, resource optimization, and resilience. Alternative feedstuffs, especially fishmeal alternatives such as plant protein mixtures, insect meal, and single-cell protein. In addition, technology-driven solutions, including smart systems, precision aquaculture, and the adoption of sustainable practices, can help balance aquaculture growth with environmental conservation. Finally, policymakers and industry stakeholders must prioritize best practices, certification schemes, and technological innovations to ensure that aquaculture's expansion aligns with planetary environmental health objectives. In this review, challenges and promising solutions for more sustainable aquaculture will be deeply discussed.

**Keywords:** Technology driven solution, IMTA, precision aquaculture, resource use, aquaculture, sustainability, food security.

## 1 Introduction:

Aquaculture now supplies more than 50% of the world's aquatic products and is considered the fastest growing emerged food production sector (FAO, 2022). The demand for aquatic products (fish, crustaceans, mollusks, and algae) in continuous increase driven by increasing world populations and shifting consumer preferences toward healthy protein and omiga-3 rich diets (Boyd et al., 2022). However, the capture fisheries, which was the main source of seafood in the last decades, has a major drawback and experienced overexploitation, habitat destruction (Jennings et al., 2016), and climate change impacts such as ocean warming and acidification (Dobretsov et al., 2019). Consequently, aquaculture represents the real opportunity to provide enough aquatic products and at the same time overcome the decline of wild caught fish (Turlybek et al., 2025). The role of aquaculture in global food security cannot be overstated, especially in developing countries, where the other animal proteins are expensive or scary (Perera et al., 2024). Fish and other aquatic products are vital sources of high quality protein, unsaturated fatty acids, vitamins, and micronutrients (Ahern et al., 2021).

In addition, small-scale aquaculture can support rural areas and coastal communities in developing nations by introducing chance for employment, stable income to improve livelihoods and economic diversification (Perera et al., 2024). In these nations, low-tech fish farms (Araujo et al., 2022), integrated fish-rice production (Mariyono, 2024), and low-trophic species cultivation such as mollusks, algae, and seaweeds could offer developable solutions that enhance local food security and reduce over-reliance on imported foods (Slater & James, 2023).

However, the expansion of non-controlled aquaculture could negatively impact the ecosystem in surrounding water bodies (Kunzmann et al., 2023). The effect of aquaculture, however can reduce the pressure on fragile marine ecosystems, could causes serious ecological concerns, such as organic matter pollution from the wastes and non-eaten foods, chemicals, hormones (Grzegorzek et al., 2024), destruction of natural habitats of fry fish (mangrove clearance, coral reef damage, and seagrass forests death) (Teena Jayakumar & Sarkar, 2024), and disturbance of natural biodiversity due to escaped non-native species (Raj et al., 2021). Therefore, aquaculture growth must be carefully governed to avoid replicating the environmental mistakes of industrial agriculture.

Another major drawback of aquaculture sustainability is the source of feed ingredients. Until now, the main protein source in the diet of fish, especially carnivorous species, is fishmeal and fish oil which come from the wild caught fish (Qian et al., 2024). This could increase the pressure on the fisheries even for the nonedible fish species (Oliva-Teles et al., 2022). Furthermore, fishmeal production declines in response to general deterioration in fisheries, which could cause supply fluctuations, increase price, and reduced quality of the fishmeal present (Zaretabar et al., 2021).

On the other hand, sustainable aquaculture could mitigate some of the environmental pressure associated with conventional food production and has the potential to a wider food landscape (Little et al., 2016). Compared to terrestrial livestock production, aquaculture has a lower carbon footprint per kg of protein production (Froehlich et al., 2018). This merit is attributed to an efficient feed conversion ratio, which could reach 1.5% and lower greenhouse gas emissions associated with aquatic farming practices (Diken et al., 2022). For instance, the carbon footprint of rainbow trout is estimated as 1.69 kg $CO_{2eq}$/kg of produced fish (Diken et al., 2022). Furthermore, for Nile tilapia, it estimated 2.03 kg $CO_{2eq}$/kg of protein (de Melo Júnior et al., 2025). Most of the carbon emissions from aquaculture come from aquatic feed production by 73.69% of total emissions, while the other amount comes from management, biofiltration, and transportation (Diken et al., 2022). Furthermore, some aquaculture practices and types provide ecosystem services, such as seaweed farming that create habitats for marine species and has high carbon sequestering efficiency (Krause-Jensen et al., 2018) and globally 50% of carbon sequestering was conducted by the oceans (Chung et al., 2018). Moreover, bivalve cultivation in a multitrophic system improves water quality (Granada et al., 2018). The sustainable growth of aquaculture is a balance among several challenges and innovative sustainable solutions (Fig. 1).

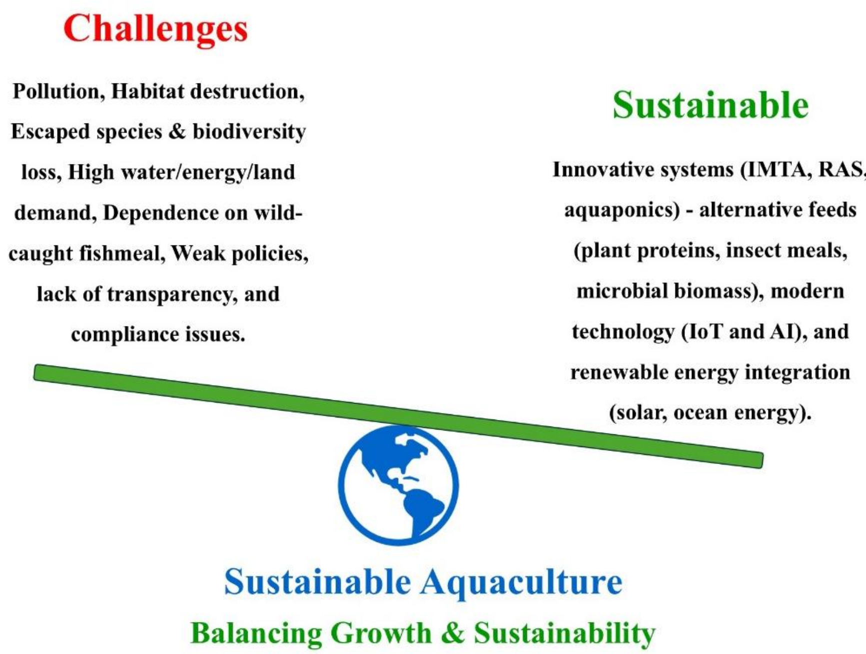


**Fig. 1.** Sustainable aquaculture, challenges, and solutions balance.

## 2 Challenges of sustainable aquaculture

### *2.1 Pollution*

Sustainable aquaculture practices face several key environmental challenges, including pollution, habitat degradation, resource conflicts, and regulation gaps. One of the direct environmental effects of aquaculture on ecosystems is the pollution of discharge water, this effluent is rich in nutrient (nitrogen, phosphorus, and organic matters) (Grzegorzek et al., 2024). The surrounding water bodies generally suffer from eutrophication and harmful algae blooms that could threaten aquatic animal life (Trottet et al., 2022). Antibiotic misuse or excessive use could also negatively affect aquaculture sustainability, whereas this chemical accumulates in the animal body and could reach the final consumers, also it induces disease resistance bacteria for aquatic or terrestrial animals (Shao et al., 2021). The emerging of disease resistance or multiresistance microbes is estimated as the main cause of death for more than 700 thousand around the world (Talebi Bezmin Abadi et al., 2019).

Other chemicals used, such as pesticides that are used to control fungal and parasitic infections such as malachite green, copper sulfate, methylene blue, and trifluralin (Boyd & Massaut, 1999). However. these compounds have desirable effects on aquaculture, could threaten natural fauna and biodiversity (Roy et al., 2021). In addition, formaldehyde, potassium permanganate, chlorine and chlorine-containing compounds, and iodine have been used in aquaculture as disinfectants to maintain hygiene throughout the production cycle and decrease disease outbreaks (Rico et al., 2012).

Aquaculture also causes hormonal pollution, especially due to the release of steroidal hormones with untreated wastewater discharge (Nugegoda & Kibria, 2017). The hormones used in aquaculture are used mainly for induce sex reversal for tilapia and many other cultured species (M Zaki et al., 2021). These hormones could affect the natural sex ratio in ecosystems or accumulate in the fish body and finally reach the food chain and pose health risks to humans (Zahran et al., 2020). Natural and synthetic hormones can alter endocrine function and negatively affect reproduction in aquatic animals (Ojoghoro et al., 2021). Hormonal pollution could also affect non-target species, such as cyanobacteria and cause growth inhibition at a high level, especially in combined hormone exposure (Czarny et al., 2019).

### *2.2 Resource use (Energy, water, and land)*

As in other agriculture projects, aquaculture has significant resource challenges such as feed, water, energy, and land. A large amount of balanced formulated feed is required for aquatic farmed species, which required incorporating fishmeal as a protein source (Boyd & McNevin, 2024). In addition, a low feed conversion ratio increases feed consumption, leading to increased feed purchases and environmental impacts (Buttle et al., 2024).

High water use in extensive or open intensive systems is another challenge for aquaculture, especially freshwater farming in different countries that have water scarcity (Costa-Pierce et al., 2010). The water need in the semi-intensive carp production system as an example calculated as 10.3 $m^3$/Kg including evaporation loss (15%), seepage loss (11%), and water exchange requirements (74%) (Sharma et al., 2013). Also, aquaculture production is calculated based on a water surface area basis, however, land required as embankments, roads, storage areas (Pueppke et al., 2020). Jescovitch et al. (2016) calculated the land-to-water surface area ratio in hundreds of fish farms and found the average is 1.48, which decreased with increasing pond size.

Energy use varies across aquaculture systems, with low trophic level systems being more comparable to terrestrial agriculture in efficiency, while intensive and super-intensive systems like shrimp aquaculture are highly energy-intensive (Troell et al., 2004; Costa-Pierce et al., 2010). The energy requirement for agriculture, aquaculture, fishing and forest was estimated to be around 30% of the society’s energy supply (Marshall & Brockway, 2020). Resource use differs from aquaculture system and animal type to other, in animal project, 45–90% of the sources related to feed requirements, while in the seaweed project, 83–99% are linked to the energy and maintenance activities (Marín et al., 2019).

### *2.3 Regulations gap*

With the expanding global population and climate change sustainable aquaculture has inevitable consequences. However, there is still a world wild gap in regulations that organize or delay the development of sustainable aquaculture (Renwick, 2016). This problem increased in developing countries, especially in small-scale farms, while the understanding of aquaculture-environment interaction is underdeveloped, leading to inadequate regulations. Also, the focus is on regulations for the culture of finfish rather than shellfish (Black & Cromey, 2008). One other obstacle is the lack of transparency in supply chains, where the product volume, the source of the product, and the conditions of production are not reported, in addition to the absence of a project license and quality assurance certificate (Jonell et al., 2016).

In Southeast Asia, weak or absent regulations in shrimp farming led to dramatic deforestation of mangrove and increased vulnerability to coastal erosion and storm surges (Richards & Friess, 2016). Meanwhile, in most of the European Union countries enforce stricter rules under the Common Fisheries Policy, including habitat protection and effluent limits, but even these regulations face compliance challenges (Luo et al., 2023). For example, in Nordic countries, several policies focused on aquaculture diet production and environmental sustainability, however, it needs more improvement to meet increased of intensification and enhanced profitability (Luthman et al., 2022).

## 3 Innovative sustainable solutions

With the inevitable need to increase aquaculture production, this expansion must be carefully managed to reduce the potential environmental risk. In this section the promising solution for more sustainable aquaculture will be discussed (Laktuka et al., 2023).

### *3.1 Integrated aquaculture systems*

Integrated systems play a key role in advancing sustainability by fostering efficiency, resource optimization, and resilience. For example, aquaponics which combine fish farming with hydroponic crops, the nitrogen supply for plant growth come from fish excretion and uneaten feed, that minimizes the use of nonrenewable resources and improve water quality and increase economic benefits (Tyson et al., 2011). Smart aquaponic system are developed using sensors, actuators, microcontrollers, and microprocessors to manage all aquaculture practice and react with any abnormal condition to become self-sustainable and cost-effective farming (Shafeena, 2016). However, aquaponic is the highest sustainability system compared to conventional aquaculture by reduced resource consumption and fewer environmental impacts, its major application is still practicing as a hobby or non-profit organizations (Colt et al., 2022).

Recirculating aquaculture systems (RAS) offer a solution by introducing an efficient use of space and resources while increasing production (Martins et al., 2010). It also introduces an efficient way for recycling nutrients through integrated farming, controlling wastes, and spreading of infectious diseases to the natural water bodies (Aich et al., 2020). RAS improve biosecurity by isolating farmed fish from natural ecosystems, so it can be a good solution (Lal et al.). However, challenges such as high investment costs and technical knowledge gaps remain (Midilli et al., 2012).

Integrated multi-trophic aquaculture (IMTA) offers numerous benefits that make it a promising approach for modern sustainable aquaculture practices. By integrating species from different trophic levels, such as seaweeds and shellfish, that can help in biomitigation by absorbing excess nutrients, thus maintaining ecological balance (Bueno, 2021). IMTA reduces the ecological footprint of aquaculture by using waste products from one species as inputs for another, to minimize pollution and nutrient loading in natural environments (Sukhdhane et al., 2018; Rusco et al., 2024). IMTA enhances economic stability through product diversification, reducing production and market risks associated with monoculture systems (Alam et al., 2024). Moreover, IMTA systems are socially acceptable and align with consumer preferences for environmentally responsible products, potentially leading to better market access and premium pricing (Hossain et al., 2022). The system supports the livelihoods of coastal communities by providing a sustainable source of food and income, contributing to the broader goals of the blue revolution (Alam et al., 2024).

### *3.2 Alternative feedstuff*

Feed sustainability is a major sustainability concern, as many aquaculture systems depend on fishmeal and fish oil derived from wild-caught forage fish, creating a paradoxical strain on marine resources (Aksnes et al., 2017). Innovations in alternative feeds, such as plant-based proteins, insect meals, and microbial biomass, are essential to reduce dependence on wild fish and improve the ecological footprint of the sector. Furthermore, farming species that feed low in the food chain could optimize resource use (Costa-Pierce et al., 2010).

The integration of plant-based proteins into aquaculture is increasingly recognized as a sustainable alternative to traditional fishmeal, addressing both ecological concerns and economic viability. Research indicates that various plant protein sources can effectively replace fishmeal partial or even totally (Han et al., 2022), and in several studies it is enhancing growth performance and maintaining fish health while reducing environmental impacts (Mugwanya et al., 2023). Furthermore, to enforce the benefit of a plant protein-based diet, the use of locally available plant ingredients could reduce reliance on fishmeal, which faces supply and price challenges (Hussain et al., 2024). Moreover, replacing fishmeal with plant proteins can significantly lower feed costs and enhance profitability (Akter et al., 2024). However, there some practical practices could be considered to enhance the utilization of plant protein sources, such as enzymatic, heat treatments, and fermentation to neutralize the anti-nutritional factors, beside the diversify the protein sources to overcome the lack of amino acids deficiency (Hussain et al., 2024).

Insect meals are emerging as a sustainable alternative to traditional fishmeal in aquaculture, addressing the growing demand for protein while mitigating environmental impacts (Fantatto et al., 2024). Research indicates that insect meals, particularly yellow mealworms and black soldier flies, can effectively replace fishmeal in aquafeeds, promoting fish growth and health. It has a favorable amino acid profile (Hasan et al., 2023), maintains n-3 fatty acid levels comparable to fishmeal (Ido et al., 2024) and positively influence fish gut microbiota, enhancing nutrient metabolism and immune responses (Hasan et al., 2023). Insect meals represent an efficiency resource reuse by utilizing organic waste, contributing to a circular economy and reducing reliance on finite resources. In addition, insect meals production has a significantly lower carbon footprint and environmental impact compared to traditional fishmeal production (Röthig et al., 2023; Auzins et al., 2024).

Another sustainable feed ingredients in the aquatic diet are microbial biomass, which improves nutrient recycling and reduces environmental impacts. For instance, single cell proteins and oils derived from microbial sources provide essential nutrients, enhancing the immune response and growth rates in farmed fish (Akpoilih, 2023). The integration of microbial-based systems, such as biofloc technology, allows for the conversion of waste nutrients into valuable feed components, thereby supporting fish and shrimp production while minimizing resource use (Zafar & Rana, 2022; Liu et al., 2025). This approach not only improves feed efficiency but also contributes to the overall health and growth of aquatic species. In addition, microbial biomass can significantly lower feed costs, since it replaces traditional fish meal and oil, which are becoming scarce (Akpoilih, 2023). Microalgae and other microbial sources have a low carbon footprint and can contribute to wastewater treatment, aligning with the principles of circular economy (Osorio-Reyes et al., 2023). The selection and management of feed ingredients are crucial because they embody substantial amounts of these resources. Efficient feed management, particularly reducing the feed conversion ratio (FCR), is essential to minimize resource use and environmental impact (Boyd et al., 2022).

### *3.3 Technology-driven aquaculture*

Although aquaculture faces challenges in resource use, advances in technology and management practice offer potential solutions. The development of more efficient smart systems, precision aquaculture, and the adoption of sustainable practices can help balance the industry growth with environmental conservation (Ohia, 2025). Smart systems in aquaculture improve sustainability by using sensors and real-time data analytics to monitor water quality parameters, such as pH, temperature, and dissolved oxygen, with less human monitoring. This technology enables timely interventions and minimizes environmental impact, supporting long-term viability (Jayandan et al., 2024).

The integration of internet of things (IoT), artificial intelligence (AI), and cloud computing in aquaculture to enhance fish production, biodiversity, and waste reduction, ultimately supporting sustainable development goals by addressing environmental challenges through innovative digital technologies (Kathuria et al., 2024). In addition, utilizing stable ocean conditions and innovative technologies like floating buoys and solar-powered LEDs to enhance macroalgae growth, significantly reducing energy consumption and improving energy return on investment in aquaculture sustainability (Chen et al., 2024).

## 4 Conclusion

Sustainable aquaculture can help meet the global food demand for high-quality animal protein while protecting ecosystems. To achieve this sustainable growth, there are several obstacles that need to be addressed, including pollution, resource use, and regulation gaps. In addition, this growth is driven by the implementation of novel solutions to improve aquaculture practices and efficiency and, in the main time, reduces environmental impacts, such as integrated aquaculture systems, alternative feed sources, and technology-driven aquaculture. However, the way still needs much effort in the case of tailoring regulations that could balance the sustainable need and profitability to assure food security.

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**Authors Contribution:**

Abdallah Tageldein Mansour: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing-Original Draft, Writing-Review & Editing

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There is no conflict of interest to declare.

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