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Emerging Innovations in Aquaculture: Navigating towards Sustainable Solutions

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Review Article

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ABSTRACT

Aquaculture, as a rapidly expanding sector of global food production, faces increasing scrutiny regarding its environmental impact and sustainability. Emerging technologies are frequently created with the aim of lessening certain negative effects caused by current aquaculture systems. Climate change poses an additional challenge to freshwater aquaculture. The effects of climate change on

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freshwater aquaculture are more intricate compared to those on land-based agriculture. Recycling nutrients, or reusing nitrogen, using various polyculture systems may be a more viable and efficient option than managing or treating the effluents linked to conventional, intense monoculture method. The Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), selective breeding, aquaponics, alternative feeds, precision aquaculture, offshore aquaculture, genetic technologies, closed containment systems, and certified sustainable aquaculture. Innovations like probiotics, RNA interference, and cleaner fish are being used to prevent diseases in aquaculture and reduce reliance on antibiotics. Precision aquaculture uses sensors, data analytics and AI to optimize fish health, feeding, and water quality in aquaculture systems. It improves efficiency and sustainability. These innovations collectively represent a paradigm shift towards more environmentally friendly and economically viable aquaculture practices. The aim of this review article is to highlight emerging innovations in aquaculture that are contributing to the development of sustainable solutions for the industry. The article focuses on various cutting-edge technologies and practices that are improving the efficiency, environmental sustainability, and overall quality of aquaculture products. These innovations are making aquaculture more productive, efficient, and sustainable as it continues to grow to meet rising global demand for seafood.

Keywords: Fish; aquaculture; climate change; renewable energy; sustainable.

1. INTRODUCTION

Aquaculture is the most rapidly expanding sector in the food industry worldwide, experiencing significant growth in the last half-century to satisfy the global need for seafood. Aquaculture output, encompassing finfish, mollusks, and crustaceans, presently constitutes over 50% of the global fish food supply [1]. Presently, the global community is confronted with a pressing dilemma of providing sustenance to the expanding populace, which is projected to reach 9.6 billion individuals by the year 2050. In order to ensure global food and nutritional security, it is essential to focus on three key areas: expanding sustainable food production, enhancing the nutritional quality of food, and minimizing food waste. This is particularly important considering the growing scarcity of resources such as land and water that are crucial for food production [2]. Amidst this difficult circumstance, aquaculture is emerging as a vital method of producing food.

The progress of human civilization has been greatly influenced by the process of domesticating plants and animals for the benefit of our species. Agriculture and animal production have been practiced for thousands of years and are seen as fundamental to the advancement of civilizations. The fish biochemistry and biotechnology approaches to fish nutrition and the health status of fish [3,4]. Aquaculture is the term used to describe the deliberate cultivation of aquatic creatures. While the domestication of certain aquatic creatures has existed for centuries, humans have primarily relied on the fisheries industry to meet their need for seafood and other resources derived from aquatic sources. Aquaculture only recently emerged as a substantial provider of food, accounting for over 50% of the fish and shellfish consumed by humans. It has also become a crucial element in certain area economies [5,6].

Aquaculture can only grow sustainably if the interplay between environmental, social, and economic aspects is properly considered [7]. Sustainable aquaculture has given many coastal and rural communities a boost economically, which is especially helpful in places where long-term economic growth is a challenge [8]. Still, passionate user group conflict has occasionally occurred in these communities when aquaculture has been introduced into regions that were previously mostly used for commercial fishing and a range of recreational activities. A well-thought-out strategy for rural economic and social development that involves all members of the community is necessary to rectify this disparity. Efficient research, development, monitoring, and incentive programs can help achieve sustainable economic development while also protecting ecosystems and promoting social justice. This approach to watershed and coastal management is essential for preserving ecosystem integrity and striking a balance between human values [9,10]. Recycling nutrients, or reusing nitrogen, using various polyculture systems may be a more viable and efficient option than managing or treating the effluents linked to conventional, intense monoculture methods. While phytoplankton and zooplankton fill substantial niches in the production pond's respiratory system (their ability to use oxygen), they are worthless to vendors. These niches could be filled with economically valuable species grown through polyculture if filter-feeding fish and mollusks are carefully chosen. Instead of going bankrupt due to the new regulations on effluent discharge from intensive monoculture production ponds, it could be better to cultivate channel catfish alongside paddlefish and different kinds of freshwater mussels. For the aquaculture business to thrive in the face of a growing human population and the rapid depletion of non-renewable resource supplies, adaptation is key to sustainability [11,12]. Periphyton is group comprises algae, zoological and filamentous bacteria, attached protozoan, bryozoan, rotifers as well as free-swimming microorganisms [13].

Emerging technologies are frequently created with the aim of lessening certain negative effects caused by current aquaculture systems. However, it is important to note that these technologies may inadvertently transfer the environmental burden by amplifying other significant types of consequences [14]. Developing closed systems primarily focuses on minimizing nutrient emissions in open waters, which can lead to eutrophication. However, creating a fish-friendly environment in these closed systems often requires a significant amount of energy. If this energy comes from fossil-based sources, it can contribute to the impacts of climate change [15]. Furthermore, research conducted by Bohnes et al. [15] has revealed that feed is the primary factor responsible for environmental consequences in aquaculture sources. A wide range of feed components, such as fish meal, soybean meals, and insect-based meals, are available for farmers to choose from. Each of these ingredients is associated with distinct environmental implications [16]. It is crucial to prioritize minimizing environmental impacts when developing aquaculture by selecting technologies and feed sources that have reduced environmental loads.

2. SELECTIVE BREEDING FOR IMPROVED DISEASE RESISTANCE AND GROWTH

Selective breeding is a powerful technique used to enhance desirable traits in plants and animals. Selective breeding is essential for enhancing disease resistance and boosting the overall health and production of both land-based livestock and farmed aquatic species [17]. Griot et al. [18] reported the impact of population size and marker density on disease resistance traits prediction accuracy in European sea bass and gilthead sea bream. It found that adding a QTL effect improved accuracy, suggesting genomic selection for aquaculture. Disease resistance breeding involves selective mating to produce or enhance disease-resistant traits in populations. It is also used more broadly for breeding disease tolerance. The goal is to create offspring that can better withstand pathogens and diseases [19]. Disease resistance traits are more complex to improve compared to traditional production traits like growth. Unlike growth, there is no straightforward method to measure host resistance. Animals must be exposed to pathogens and develop disease to accurately assess their resistance. Maintaining specific pathogen-free animals in the breeding population often prevents selecting broodstock based on survival from disease challenges [20]. Selective breeding programs with well-defined breeding objectives have led to significant improvements in terrestrial livestock production. For example, since 1960, the average 56-day-old broiler weight has quadrupled, with 85-90% of the improvement attributed to genetic enhancement. Similarly, Holstein milk yield has doubled due to genetic improvements. In farmed aquatic species, genetic improvement is still in its infancy, but there is consensus on its potential for enhancing growth, carcass composition, and feed efficiency [21]. Selective breeding is a long-term approach that accumulates small-to-moderate gains over generations. These incremental improvements are cumulative and permanent within the population. In the selective breeding for disease resistance is a vital strategy to enhance animal health and productivity. While challenges exist, ongoing research aims to improve disease resilience in livestock and aquaculture species [22].

3. CLOSED-CONTAINMENT SYSTEMS: ENHANCING ENVIRONMENTAL PERFORMANCE

Enclosed containment systems show great potential in improving environmental performance, especially in the field of aquaculture. In general, intensification can worsen certain environmental issues, such as acidification, eutrophication, and freshwater ecotoxicity. However, it can also decrease other concerns, like freshwater consumption [23]. To fully harness the potential of aquaculture in promoting beneficial changes in the food system, it is necessary to accurately assess the environmental impact of various production systems and implement measures that enable the expansion of sustainable aquatic farming to promote healthy and sustainable diets [24].

Conventional coastal aquaculture farms commonly utilize open net cage farming technologies. Regrettably, these technologies render farms susceptible to environmental hazards. Instances of problems encompass plankton blooms, which can result in fish mortality and economic detriment, as well as occurrences such as oil spills and trash discharge. In addition, climate change causes an increase in water temperature, which might potentially result in higher rates of fish diseases and mortality due to increased stress and presence of pathogens [38]. Closed containment systems offer a solution to tackle these difficulties in aquaculture. In these systems, fish are reared in a controlled environment, separated from external aquatic influences. Temperature and oxygen levels can be accurately regulated. These systems integrate offshore and maritime technology with recirculating aquaculture technology. The Eco-Ark, a pioneering model, occupies approximately 1,400 square meters of marine area. With a workforce of just two individuals, this operation has the capacity to generate an impressive 166 metric tonnes of fish per year. Eco-Ark enhances disease resilience and environmental protection by housing fish in isolated tanks, apart from the external environment [39].

Table 1. Environmental cleanliness within aquaculture systems

Aspect	**Description**	**References**
Aquaculture	Aquaculture technique used (e.g., open-pen, land-based recirculating systems, aquaponics)	Laine et al. [25]
Environmental Impact	Environmental effects, such as habitat alteration, water pollution, or biodiversity loss	Sahoo and Goswami [26]
Water Quality Management	Strategies and technologies employed to maintain high water quality standards, including filtration, aeration, and water circulation systems	Lal et al. [27]
Waste Management	Managing and treating organic waste, excess nutrients, and chemical pollutants generated within aquaculture systems	Hajam et al. [28]
Endocrine disrupting chemicals	Endocrine disrupting chemicals (EDCs) threaten fish populations, aquatic habitats, and human health	Ramasre et al. [29]
Biosecurity	Preventing spread of diseases and pathogens among aquatic organisms within the aquaculture system	Subasinghe et al. [30]
Sustainable Feed	Utilization of sustainable feed sources and feeding practices to minimize environmental impact and optimize nutrient utilization	Chisoro et al. [31]
Energy Efficiency	Energy-efficient technologies and renewable energy sources to reduce energy consumption and greenhouse gas emissions	Heydari et al. [32]
Sustainable Practices	Sustainable practices employed to minimize negative impacts on environmental health, including waste management and habitat conservation	Roy et al. [33]
Environmental Monitoring	Monitoring environmental parameters like water quality, habitat health, and ecosystem resilience	Forio and Goethals, [34]
Ecosystem Preservation	Preserve and restore natural ecosystems impacted by aquaculture activities, such as mangrove protection or reef restoration	Overton et al. [35]
Nanotechnology sustainable	Nanotechnology approach for sustainable fisheries and aquaculture such water quality and feed utilization	Lal et al. [36]
Fish Health Assessment	Detecting fish diseases with biosensors, next-generation sequencing, and immunochromatography	Yadava et al. [37]

4. INTEGRATION OF RENEWABLE ENERGY SOURCES IN AQUACULTURE OPERATIONS

The integration of renewable energy sources into aquaculture operations is a progressive strategy that has significant promise for promoting sustainable and eco-friendly practices [40]. Renewable energy refers to energy derived from natural processes that are consistently renewed, such as sunlight, geothermal heat, wind, tides, water, and other forms of biomass. This energy is inexhaustible and continuously replenished. Renewable energy, sometimes known as "clean energy" or "green power," is characterized by its lack of environmental pollution. The utilization of renewable energy in aquaculture decreases production expenses and enhances sustainability. There are numerous applications of renewable energy sources in aquaculture [41]. Live food is used as a larval feed to help for the highest survival of the larval stage of fish . HUFA and vitamin C enriched live food is a very useful larval feed for fish [42-44]. Koričan et al. [45] examines the environmental and economic aspects of aquaculture systems, focusing on renewable energy sources (RES) and their use in aquaculture farms and vessels. It identifies energy needs and performs Life Cycle Assessments (LCAs) on different power system configurations. Electrification of farm vessels is seen as a solution to reduce environmental footprint and operating costs, but it requires larger investment and may cause financial losses if an unfavorable RES is chosen.

Aquaculture, which involves the cultivation of aquatic organisms, has become a significant contributor to global food security. However, the sustainability of traditional aquaculture practices has been a concern due to overfishing and environmental impacts. The integration of renewable energy systems offers a way to address these challenges [46]. Aquaculture farms can reduce their dependence on fossil fuels and decrease greenhouse gas emissions by utilizing renewable energy sources. Renewable energy sources such as wind, solar, and wave power can provide a consistent and reliable energy supply for aquaculture operations. Over time, investing in renewable energy infrastructure can lead to cost savings compared to conventional energy sources [47]. These technologies, including tidal and wave energy, can be harnessed to power offshore aquaculture systems. Co-locating offshore wind farms with aquaculture facilities can create synergies and shared infrastructure, reducing costs and environmental impact [48].

5. BIOTECHNOLOGY AND GENETIC ENGINEERING IN AQUAFEED DEVELOPMENT

Numerous obstacles will be encountered in the next ten years by aquaculture, the practice of cultivating aquatic creatures. Fighting illnesses, raising better broodstock, creating suitable diets, and controlling water quality are all examples of these difficulties. According to Taysi and Kirici [49], biotechnology is vital for improving aquaculture sustainability and productivity in the face of these issues. In order to improve aquaculture and meet demand, it is highly recommended to apply current biotechnology to increase output of aquatic species. Although there is a lot of debate and danger associated with genetic modification and biotechnology, it does have the ability to increase the number and quality of fish raised in aquaculture. Genetically engineered feed ingredients and transgenic fish are potential solutions to reduce fish meal and oil dependency, while also improving production efficiency and product quality. These technologies are revolutionizing food production, reducing pressure on wild fish stocks, preserving aquatic ecosystems, and improving nutritional profiles of farmed fish [50]. Biotechnology has great promise for improving culture organisms' reproductive capabilities and their early developmental outcomes. Both the aquaculturists and the people who buy their products stand to gain from the technology's many applications in the industry. Transgenics, feed sources, and feed composition improvement are areas of biotechnology in aquaculture. Improvements in growth rates and reproductive cycle control through hormone therapy are two additional biotech applications in aquaculture. Other biotech applications include vaccine production, genetic resource conservation, enhancement of unique biomedical models, and disease resistance in fish [1].

The aquaculture industry has been slow to adopt genetic enhancement projects, in contrast to the plant and livestock industries. Genetic improvement has only been applied to a tiny fraction of farmed aquatic species. Genetic enhancement improved feed conversion efficiency, reducing resource consumption and environmental impact. This promotes sustainability by minimizing feed waste and nutrients excretion in aquaculture operations [51]. On the other hand, genetics and biotechnology provide tremendous promise for improving aquaculture's output while simultaneously reducing its environmental impact. The success rate of cultured organisms' reproduction and early development can be improved by the use of biotechnological methods. Furthermore, they have the ability to prolong the availability of gametes and fry [52]. Modern biotechnologies in aquaculture are based on rapidly evolving knowledge of molecular biology and genetics. These technologies can optimize safe innovation in aquaculture, considering the diversity of species cultured and various production systems. Responsible technology transfer ensures protection of wild aquatic diversity and minimizes impacts on rural and subsistence populations [53]. Developing the necessary knowledge for biotechnological innovation in aquaculture is essential. Biotechnology contributes to food security, poverty alleviation, and income generation. Balancing technological advancements with environmental and social considerations is crucial [54].

6. BLOCKCHAIN TECHNOLOGY FOR TRACEABILITY AND TRANSPARENCY

The use of blockchain technology in the seafood industry can provide a reliable means of ensuring transparency in the supply chain and promoting sustainable practices over an extended period of time [55]. The technology of blockchain has the potential to completely transform the way businesses are currently conducted. This technology has the potential to enhance supply-chain transparency within the fishing industry, thereby aiding in the prevention of illegal activities, improving supply-chain coordination, increasing operational efficiency, enhancing sustainability performance, and detecting market trends [56,57]. Blockchain, a decentralized system for recording and verifying transactions, is transforming the seafood business by improving the capacity to track and verify the origin and movement of products along the supply chain [58].

Blockchain is a new technology that has been employed in recent years to help value chain operators coordinate their efforts. Blockchain is a distributed ledger technology that records transactions including value, knowledge, or digital events and allows participants to access and validate them without the need for a central authority [59]. Blockchain enables real-time monitoring of seafood as it moves along the supply chain. Coupled with the Internet of Things (IoT), it connects data from fishing vessels to processors, ensuring transparency at every stage. This transparency eliminates uncertainty and addresses sustainability and food safety concerns [60]. By recording transactions in an immutable and decentralized ledger, blockchain streamlines processes. It simplifies record-keeping, reduces paperwork, and minimizes errors. Efficient supply chains benefit producers, distributors, and consumers alike. Blockchain can verify the origin of seafood products, ensuring they are sustainably sourced. Consumers can access detailed information about the fish they purchase, including catch location, fishing methods, and certifications. This promotes responsible consumption and supports environmentally friendly practices [58].

7. WATER TREATMENT INNOVATIONS FOR IMPROVED WATER QUALITY MANAGEMENT

Water On, a cutting-edge smart metering and automated leakage prevention system, is revolutionizing water management. There are environmental issues about the water contamination caused by aquaculture wastewater (AWW) and the excessive usage of wild fish populations as ingredients in fish feed [61]. Aquaculture effluents, including as uneaten feed and feces, contain organic components that contribute to the degradation of both the water bodies and sediments in which they are released [62]. The primary constituents of aquaculture wastewater that might cause environmental problems and hinder fish growth are dissolved and particulate organic matter, total dissolved solids, and nutrients like phosphate and nitrogen [63].

1. Installation and Integration: WaterOn is installed at the point where water enters a building or apartment complex. It integrates seamlessly with existing water supply infrastructure.
2. Real-Time Monitoring: WaterOn continuously monitors water flow and usage patterns. It detects anomalies, such as leaks or excessive consumption.
3. Automated Leak Detection and Prevention: When a leak is detected, WaterOn promptly shuts off the water supply to prevent further damage. This prevents wastage and minimizes losses due to leaks.
4. Smart Alerts and Notifications: WaterOn sends real-time alerts to property

managers or residents via a mobile app. Users receive notifications about leaks, abnormal usage, or potential issues.

5. Savings and Sustainability: By preventing leaks and promoting responsible water use, WaterOn contributes to significant water savings. It supports sustainable practices and reduces environmental impact.

8. REMOTE SENSING AND SATELLITE TECHNOLOGY FOR MONITORING AQUACULTURE ENVIRONMENTS

Remote sensing is essential for the surveillance and control of aquaculture ecosystems. Remote sensing can be used in aquaculture planning by integrating Earth Observation (EO) into Geographic Information Systems (GIS) and employing spatial multi-criteria evaluation (SMCE) approaches. This approach helps address intricate environmental and socioeconomic limitations in a comprehensive manner [64,65]. Remote sensing helps assess parameters like temperature, salinity, dissolved oxygen, and pH in water. By analyzing satellite images, researchers can identify changes in water clarity and detect contaminants that may affect fish health and aquatic organisms. This information aids in assessing the overall health of aquatic systems and identifying potential issues such as pollution or disease outbreaks [66]. Remote sensing techniques, including acoustic surveys, sonar, and LiDAR, allow us to detect the presence of fish in water. Fish detection helps monitor fish behavior, assess fish health, and estimate fish biomass. It also identifies areas where fish experience stress due to poor water quality or overcrowding [67].

Remote sensing allows aquaculture operators to monitor changes in farm conditions with greater accuracy and over extended periods of time. By adopting a proactive strategy, they are able to detect issues before they worsen and implement preventive measures. Remote sensing data can be utilized by farmers to enhance resource management and production cycles, resulting in optimal yield [68]. Satellite remote sensing facilitates high-resolution mapping of pond aquaculture. It supports sustainable development by providing inventory analyses for valuable coastal ecosystems [69]. The platform called “Aquasafe” constantly monitors fish farming operations and provides early warnings for potential risks. It combines satellite and in-situ data to offer comprehensive insights and alerts to farm operators [70]. Remote sensing from satellites and aerial and underwater autonomous vehicles can provide practical monitoring solutions. Small Unoccupied Aircraft Systems (sUAS) can estimate canopy area, density, and tissue nitrogen content, while underwater color imagery can be classified using deep learning models. Future developments in vehicle and infrastructure technologies are needed to reduce costs and overcome operational limitations for continuous deployment in offshore settings [71].

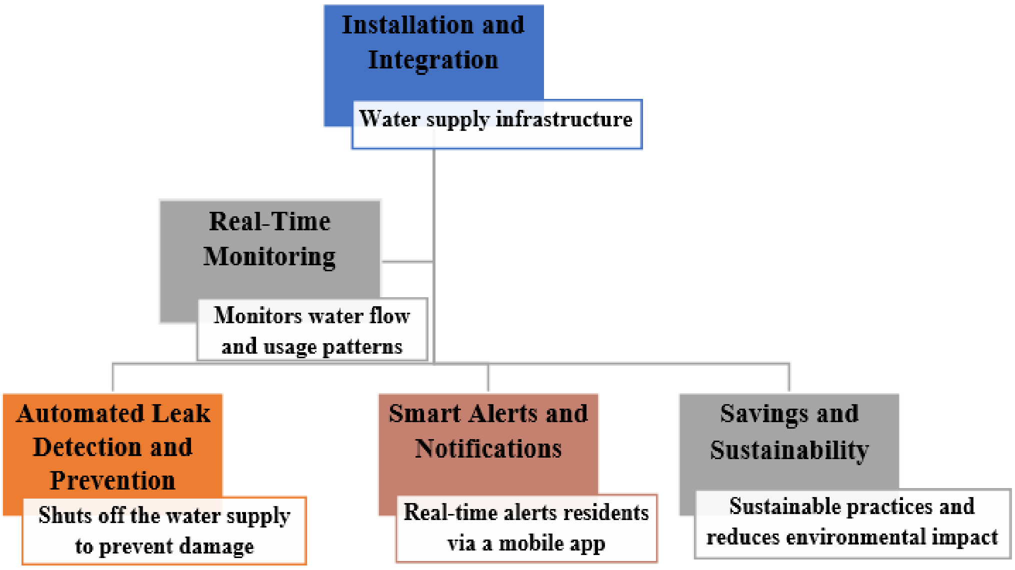

Fig. 1. Water treatment innovations for improved water quality management

9. COMMUNITY-BASED AQUACULTURE INITIATIVES FOR SOCIO-ECONOMIC DEVELOPMENT

Community-based aquaculture (CBA) has significant potential to promote socio-economic development in coastal communities. Community-based aquaculture refers to the practice of local communities managing and operating aquaculture activities within their immediate area. Community-based aquaculture contributes to the generation of income and employment possibilities, especially in rural regions, leading to a decrease in poverty and an improvement in financial resilience. Communities can help protect the environment, preserve aquatic biodiversity, and reduce negative effects on ecosystems by practicing responsible aquaculture [72,73].

Aquaculture, a rapidly growing food production sector, offers rural community development and coastal livelihoods. An ecosystem approach to aquaculture (EAA) is recommended for sustainable development, but community-based management is needed. This research explores community-based marine aquaculture (CBMA) in Nova Scotia, Canada, focusing on nonfinfish. Stakeholders support CBMA's potential for sustainable growth, but operationalizing it remains a challenge [74]. Coastal communities often face a social-ecological trap, where they heavily rely on marine natural resources for their livelihoods. CBA serves as an alternative or supplementary income-generating activity, aiming to minimize over dependence on marine resources and promote biodiversity conservation. However, despite its proliferation in the western Indian Ocean (WIO) region, the degree to which CBA achieves its objectives remains unclear [73]. Political, social, economic, technical, and cultural issues have all contributed to the increasingly complex nature of aquaculture as it interacts with other areas of food production. The technological progress, a wider variety of aquatic species and farming methods can now be utilized, giving consumers even more options. The future demand for fish and fisheries products will be influenced by a variety of factors, including population expansion, economic development, rising disposable income and purchasing power, and social factors including traditional fish consumption patterns [75]. According to Roberts and Muir [76], sustainability concerns have the potential to alter our views on what constitutes an ideal approach to aquaculture development and management. Aquaculture and integrated agriculture have been in use for nearly a century. Mixed culture (fish, pig, and poultry) and fish/poultry culture are the most common systems. Organic fertilizer from livestock manure is utilized in fish ponds, which double as waste stabilization ponds, in integrated livestock/fish farming systems, thus protecting the environment. Over the last decade, a technological divide has emerged, with relatively expensive intensive aquaculture employing formulated pellet feed gradually replacing more conventional semi-intensive aquaculture that made use of locally available and on-farm agricultural leftovers. A third technique, however, can help both large-scale producers cut costs and small-scale farmers increase fish output using inorganic fertilization and supplemental feeding. Chomnongsittathum [77] argues that this system is better for the environment than intensive farming that uses pellet feed exclusively.

10. CLIMATE CHANGE ADAPTATION STRATEGIES IN AQUACULTURE

Climate change referred to the alteration in the statistical patterns of weather occurring across time spans ranging from decades to millions of years. There is now a widespread consensus that climate change is no longer just a possible danger, but rather an inevitable outcome of two centuries of excessive emissions of greenhouse gases (GHGs) from burning fossil fuels in energy production, transportation, and industry, as well as from deforestation and intensive agriculture. Climate change poses an additional challenge to freshwater aquaculture. The effects of climate change on freshwater aquaculture are more intricate compared to those on land-based agriculture. This is because freshwater aquaculture involves poikilothermic animals, which are highly susceptible to different types of living and non-living stressors that directly impact the growth, reproduction, physiology, and behavior of fish. Climate changes have a direct impact on aquaculture by affecting fish stocks. They also have an indirect impact by altering the productivity, structure, and composition of ecosystems. Additionally, climate changes influence fish prices and the costs of goods and services needed by fishers and fish farmers, such as fish meal and fish oil [78]. Aquaculture is greatly affected by climate change, which has a substantial impact on both output and sustainability.

Marine Spatial Planning (MSP) is a strategic method that is crucial for promoting the sustainable growth of aquaculture [79]. Marine spatial planning (MSP) is a strategic and effective method for managing the increasing and diverse human activities in coastal areas and promoting their sustainable development. It is based on an ecosystem-based approach [80,81]. To ensure the sustainable development of intricate socio-ecological coastal systems, it is necessary to implement a suitable governance strategy. This strategy should be based on an adaptive ecosystem-based management approach that aims to integrate human activities with conservation goals [82,83].

11. SUSTAINABLE CERTIFICATION SCHEMES AND ECO-LABELING PROGRAMS

The world of sustainable certification schemes and eco-labeling initiatives. These activities are essential for encouraging environmentally responsible behaviors and directing customers towards more sustainable options [84]. Eco-labeling has received international endorsement as a market-based method to enhance environmental management. Nevertheless, the implementation of this approach in natural resource industries has been intricate and frequently contentious [85]. When it comes to aquaculture and the trading of ornamental fish, the main concern is whether the fish is produced using a sustainable chain of custody. The development of a certification and eco-labeling system is primarily motivated by the need to address legal and legislative challenges that fail to prioritize the environment and its resources in a sustainable manner. The inequitable access and ownership of biological resources by specific vested parties within the so-called open access system has led to the degradation of habitats and unrestricted entry of exotic species into natural water bodies [86].

1. Eco-labeling: Eco-labels are symbols or certifications that provide information about the environmental and social impact of products and services. The aquaculture industry is distinguished by a notable expansion in the variety of eco-labels with varying designs (e.g., pictures, linguistic representations, shapes, and colors) [87]. By giving customers access to environmental attribute information that they otherwise would not be able to directly witness or verify, eco-labels seek to lessen the information asymmetry that exists between producers and consumers [88,89]. According to some study, buyers are prepared to pay more for goods bearing eco-labels (such as organic, sustainable, or environmental). As consumers, eco-labels guide our purchasing decisions by revealing the "world" behind a product. They help us choose items that meet specific environmental and social criteria [90]. The importance of eco-labeling gained international consensus decades ago as part of the global push toward sustainable development. Stakeholders recognized the need for transparent, verifiable, and non-misleading consumer information tools related to sustainable consumption and production [91].

Types of Eco-labels:

ISO Type I Labels (Eco-labels): These labels identify the overall environmental preference of a product within a category based on life cycle considerations. They are awarded by impartial third parties to products that meet environmental leadership criteria. Examples include organic labels and Rainforest Alliance labels.

ISO Type I-like Labels (Certification Schemes or Sustainability Labeling): Similar to Type I labels, these focus on specific impacts (e.g., energy consumption, agricultural practices) and apply to specific sectors (e.g., energy-using appliances, agricultural commodities).

ISO Type II Labels: These are self-declared environmental labels, often representing a single attribute or a company's own environmental logo.

ISO Type III Labels (Product Declarations): These provide detailed quantitative information about products, similar to nutritional labels.

2. Commonly Found Eco-labels:

There are numerous eco-labels worldwide, each emphasizing different aspects of sustainability. Some well-known ones include:

LEED: Evaluates the environmental impacts of buildings and construction.

FSC (Forest Stewardship Council): Certifies sustainably managed forests and wood products.

Green Seal: Focuses on environmentally responsible products and services.

EU Ecolabel: Recognized across the European Union for various product categories.

12. CONCLUSIONS

The advancements outlined in this study demonstrate the significant strides made in pioneering sustainable practices within the aquaculture industry. From Recirculating Aquaculture Systems (RAS) to Certified Sustainable Aquaculture programs, each innovation contributes to a collective effort to mitigate environmental impact, enhance resource efficiency, and promote long-term sustainability. By embracing these advancements, aquaculture can evolve into a more environmentally friendly and economically viable food production system, capable of meeting the growing global demand for seafood while minimizing negative ecological consequences. However, continued research, investment, and collaboration across sectors will be essential to further refine these practices and ensure their widespread adoption. With concerted efforts, the future of aquaculture holds promise as a cornerstone of sustainable food production, providing nourishment for current and future generations while safeguarding the health of oceans and ecosystems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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