Advances in Aquaculture Technology: A Review of Sustainable Practices

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Abstract
The fastest-growing industry in food production is aquaculture, which is essential to supplying the world's protein needs. This review examines aquaculture's sustainable practices and technological developments. The industry witnessed a transition from conventional techniques to more sustainable and effective systems as worries about resource depletion and environmental degradation grew. Technologies like Biofloc, Integrated Multi-Trophic Aquaculture, and Recirculating Aquaculture Systems (RAS) decreased waste discharge and increased water use efficiency. Aquaculture operations' ecological footprint has decreased as a result of feed development innovations, especially those involving plant-based and alternative protein sources.
Furthermore, improvements in health management, such as the use of vaccines, probiotics, and improved diagnostic equipment, have significantly decreased the incidence of disease outbreaks and the use of antibiotics. Additionally, selective breeding and genetic advancement for disease resistance and quicker growth were emphasized. Government laws and international collaboration supported sustainable development, while certification programs like the Aquaculture Stewardship Council (ASC) and GlobalG.A.P. encouraged ethical behaviour.
Despite these developments, there were still issues with small-scale farmers' adoption of new technologies, high operating costs, and uneven regional enforcement of policies. In order to guarantee aquaculture's long-term sustainability, this review emphasizes the necessity of ongoing innovation, capacity building, and policy support.

Keywords: Aquaculture, Sustainable practices, RAS, IMTA, Biofloc, Feed innovation, Fish health, Certification, technologies.

1. Introduction

In India, fishing is a thriving industry with a wide range of resources and potential, and it is a very significant economic activity. Fisheries and agriculture have only been acknowledged as significant sectors since Indian independence. Over the past 50 years, the world's fish production has increased steadily, and the supply of food fish is growing at an average annual rate of 3.2 percent, which is faster than the world's population growth of 1.6 percent ("The State of World Fisheries and Aquaculture, 2012," 2013). Since its earliest uses in ancient China, aquaculture, the farming of aquatic organisms, has undergone significant change. It has grown to be an essential part of the world's food supply, supplying high-quality protein sources and addressing the depletion of wild fisheries. India is a significant global producer of fish through aquaculture. Over 10% of the world's fish diversity can be found in India. With an annual fish production of roughly 9.06 million metric tonnes, the nation currently ranks second in the world for total fish production (*FAO Fisheries & Aquaculture*, n.d.). More than one-third of the nation's 9.06 million tonnes of fish produced in 2012–2013 came from aquaculture. Carp alone accounted for up to 4.18 million of the 4.43 million tonnes of aquaculture production, which was valued at US$3.5 billion (*FAO Fisheries & Aquaculture*, n.d.). Cultivating aquatic organisms is known as aquaculture. It has been recognized as the food production system with the fastest rate of growth in recent decades, making a substantial contribution to the world's food supply (Hiney et al., 2002). Given the current environmental and demographic trends, aquaculture is essential to meeting the growing demand for protein worldwide. The demand for protein sources is rising in tandem with the ongoing expansion of the human population (Hiney et al., 2002). Global issues include dwindling amounts of land that can be used for conventional farming and dwindling numbers of wild fish. This is a good time to increase the production of new fish species, such as different kinds of cod, haddock, hake, flatfish (turbot, flounder, halibut, sole), hybrid striped bass, seabass, wolfishes, lumpfishes, and tuna. This diversification can lessen dependency on a small number of dominant species and improve food security (Hiney et al., 2002). Aquaculture's rapid growth and growing contribution to global food supplies have made research on its economic impact, sustainability, and technological advancements crucial to understanding global food security. Aquaculture has grown dramatically over the last three decades, now making up more than half of the world's seafood consumption and serving as a crucial source of high-quality protein in the face of stagnating wild fisheries (Subasinghe et al., 2012). Aquaculture has evolved from traditional practices to modern, intensive systems in Asia, which leads the world in production (M & Shakunthala, 2010). This growth is especially noticeable in Asia. Beyond just providing food, the sector is important for rural livelihoods, economic development, and poverty reduction (Little et al., 2011). A balanced approach to aquaculture's development is necessary, though, as its intensification raises questions about sustainability and environmental effects (Klinger & Naylor, 2012).
Notwithstanding its advantages, aquaculture has problems with resource use disputes, environmental deterioration, and social repercussions that have not been adequately studied in the literature (Drillet et al., 2014). When evaluating

aquaculture's sustainable contribution to food security, there is a lack of knowledge regarding the integration of economic, environmental, and technological aspects (Lazard et al., 2014; Munro, 2014). The sustainability of intensive versus extensive systems, the environmental costs of feed inputs, and the socioeconomic equity of aquaculture benefits are still topics of debate (Bunting, 2013). Furthermore, the industry's future role in global food systems is made more complex by its susceptibility to disease outbreaks and climate change (Tacon, 2010). With a focus on aquaculture's historical development and current trends in promoting global food security, this systematic review aims to synthesize current knowledge on the industry's economic impacts, sustainability issues, and technological advancements. This review seeks to close identified gaps in order to inform practice and policy for sustainable aquaculture growth that supports social and environmental objectives.

2. Historical Overview of Aquaculture Practices

Due to the growing demand for seafood worldwide, aquaculture has changed dramatically over the millennia, moving from traditional methods to more intensive ones. Early aquaculture systems, like those in Southeast Asia and ancient China, prioritized ecosystem management and sustainable practices. The "Blue Revolution," which focused on increased production and technological advancements, signalled the beginning of the shift towards intensive and semi-intensive methods in the 20th century.

Antiquity (2000 BC to AD 500): The early ideas of "Seeds in Antiquity," which imply early forms of aquaculture practices, were probably traditional and extensive in nature, with an emphasis on fish and shellfish as food sources (Nash, 2011).

Middle Ages (500-1450): The term "Subsistence Farming" refers to aquaculture when traditional and less intensive methods were used to support communities (Nash, 2011).

Early Modern Period (1450-1900): During this era, aquaculture experienced "The Slow Dawn of Science," which suggests a slow shift towards more methodical and possibly semi-intensive methods as scientific knowledge started to impact practices (Nash, 2011).

Late 18th to Early 20th Century (1750-1920): The late 18th and early 20th centuries are known as the "Roots of Modern Aquaculture" and the start of "Farming the Sea," indicating a substantial shift towards more structured and possibly larger-scale operations, which may include the forerunners of intensive techniques (Nash, 2011).

Mid-20th Century (1900-1970): Known as the "Fifty Lost Years," "Aquaculture in a World at War," and "Postwar Pioneering," It is characterized by disruptions and the ensuing attempts to innovate and grow, setting the stage for future intensification (Nash, 2011).

2.1 Traditional systems

One of the main features of traditional aquaculture is polyculture, which involves growing multiple species in the same body of water. The production of aquaculture worldwide is still greatly influenced by the polyculture of Chinese carps and other fish species in ponds (Carter, 2006). This long-term success is a result of both more recent technological developments and the techniques practitioners have developed over millennia. Aquaculture has the longest history in China, where common carp were first cultivated in earthen ponds more than 3,000 years ago (Carter, 2006). The social and environmental compatibility of traditional inland aquaculture with regional landscapes is one of its defining characteristics. It mainly uses locally accessible and on-farm wastes and byproducts as dietary inputs for aquatic organisms raised for food (Edwards, 2009). Crop/livestock/fish systems, feedlot livestock/fish integration, and rice/fish farming are examples of integrated agriculture/aquaculture systems (Edwards, 2009). Peri-urban aquaculture systems that are integrated with aquaculture-fed wastewater are one instance of this. Low-value or "trash" fish are used as feed in integrated fisheries aquaculture systems (Edwards, 2009).

2.2 Transition to intensive and semi-intensive methods

Ecologically intensive aquaculture methods were found to have a positive and significant correlation with both fisheries commodity exports and the overall trade in food commodities. This implies that the dynamics of international trade are essential to the growth of these aquaculture techniques (Longo et al., 2013). Additionally, there was a positive and significant correlation between GDP per capita and economic development, suggesting that the expansion of ecologically intensive aquaculture is correlated with economic development (Longo et al., 2013). Another factor that was found to have a significant positive correlation with ecologically intensive aquaculture practices was population size. This suggests that larger populations may drive the need for more intensive aquaculture production. The detrimental effects of intensive, pellet-fed aquaculture on the environment are being lessened by utilizing the ideas of traditional practice (Edwards, 2009). Two primary tactics are used to accomplish this: a)In situ waste reduction utilizing conventional methods to cut waste in the aquaculture system directly. b)Treatment of wastewater from intensive aquaculture operations using conventional methods (Edwards, 2009). As marine fishing became more effective during the Industrial Revolution, with the recognition of innovations like steam-powered boats and better preservation methods, aquaculture began to decline. The 20th century saw the end of this lull, though, as overfishing demonstrated that wild fish stocks could not be sustained. Aquaculture, which was first thought to be a remedy for declining wild fish stocks, saw a resurgence as a result (Smith, 2014). Advances in plastics technology made it possible to build sophisticated life-support systems, tank complexes, and hatcheries, which significantly accelerated the growth of aquaculture. Scientific tools were also essential (Smith, 2014). The aquaculture sector experienced significant cost reductions and production gains between 1971 and 1976. From roughly 1,500–2,000 pounds per acre to 3,000–4,000 pounds per acre, average annual yields increased dramatically. More intensive production was also made possible by the development of offshore platforms and net pens, which ranged in size from 1,000 to 30,000 cubic meters (Smith, 2014).

2.3 Global trends in aquaculture development (before 2014)

The substantial worldwide growth of aquaculture in the latter half of the 20th century and the first ten years of the 21st century is described by Jobling (2011)in his book. This growth represents a significant shift in aquaculture development from regional methods to a global industry. Along with details on the development of the first commercial fish hatcheries, marine research labs, and public aquariums, the text also discusses the founding, growth, consolidation, and occasionally demise of fisheries and aquaculture organizations (Jobling, 2011). Aquaculture has grown dramatically, surpassing most predictions. Global production was predicted to reach 50 million tonnes by 2020 in the 1990s. However, aquaculture contributed 52.9 million tons of the 115 million tons of fish used for human consumption in 2010, exceeding the anticipated growth levels. By 2012, aquaculture accounted for over half of the world's consumption of food fish (Smith, 2014). Aquaculture's potential to supply protein globally, reduce the strain on overfished wild stocks, and address the widening seafood trade deficit, especially in the US, is what is driving its explosive growth. Notwithstanding these advantages, pollution and the exploitation of wild fish stocks for feed are two environmental problems associated with modern aquaculture (Smith, 2014).

3. Technological Advances in Aquaculture

Technological developments in aquaculture have had a profound impact on the sector, improving species diversity, sustainability, and production efficiency. Genetic advancements, sophisticated feeding methods, and environmental management systems are some of the major innovations that have helped aquaculture become a more important source of food. Significant technological advancements in aquaculture included the use of molecular techniques for selective breeding and genetic selection, the creation of Recirculating Aquaculture Systems (RAS) for controlled environments, the deployment of Integrated Multi-Trophic Aquaculture (IMTA) for effective nutrient cycling, the use of automated and precision feeding systems, the creation of novel disease prevention strategies like probiotics and enhanced diagnostics (like LAMP), and the introduction of wireless water quality monitoring systems for real-time data.

3.1 Recirculating Aquaculture Systems (RAS)

A major development in aquaculture, recirculating aquaculture systems (RAS) provide a sustainable and regulated method of fish farming. RAS are closed-loop, tank-based systems that retain and treat water while allowing fish to be raised at high densities in regulated environments. Compared to other aquaculture systems, RAS use 90–99% less water, making them extremely environmentally friendly. They also stop fish and parasites from escaping, lessen waste discharge, and lessen the need for chemicals or antibiotics (Abdul Nazar et al., 2013).

Fig.1: Recirculating Aquaculture Systems Source: Fishery News

3.2 Integrated Multi-Trophic Aquaculture (IMTA)

A sustainable aquaculture method called Integrated Multi-Trophic Aquaculture (IMTA) combines several species from various trophic levels to produce a balanced ecosystem. By using one species' waste products as inputs for another, this strategy seeks to improve societal, economic, and environmental benefits while lowering pollution and improving resource efficiency (Cronin et al., 2013). It has been demonstrated that IMTA systems enhance nutrient cycling, lessen environmental effects, and increase economic resilience through aquaculture product diversification (Cronin et al., 2013). Byproducts (wastes) from one aquatic species are recycled to become inputs (food, fertilizer) for another using the IMTA technique (Chopin et al., 2013). Diversifying products produces a balanced system that resembles natural ecosystems, lowering its adverse effects on the environment and boosting economic efficiency. For instance, extractive organisms that can use the dissolved and particulate wastes, such as seaweed or shellfish, are cultivated with fed aquaculture species, such as fish (Chopin et al., 2013).

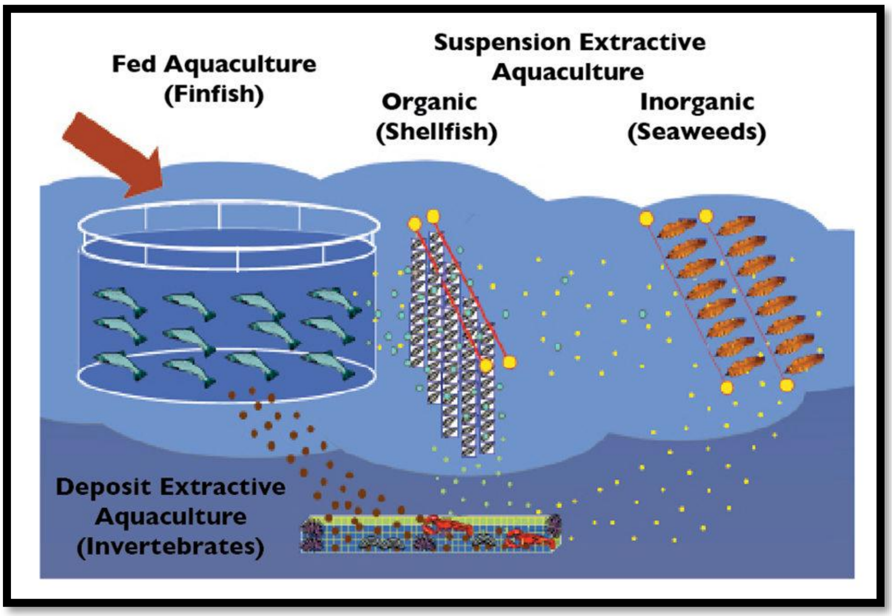

Fig.2: Integrated Multi-Trophic Aquaculture

3.3 Biofloc Technology

A sustainable aquaculture method called Biofloc Technology depends on the growth of microbial flocs in the culture water. These flocs, which are made up of bacteria, algae, protozoa, and other microorganisms, turn metabolic waste products (such as ammonia) and leftover feed into microbial protein (Chim et al., 2014). The cultured aquatic animals then use this protein as an extra food source, which increases feed conversion ratios, decreases water exchange, and improves biosecurity by inhibiting harmful bacteria. Strong aeration is usually necessary in BFT systems to maintain high dissolved oxygen levels and keep the flocs suspended (Chim et al., 2014). When compared to Clear Water (CW) or Earthen Pond (EP) systems, BFT has been demonstrated to improve shrimp reproductive performance and larval quality dramatically. Traditional extensive rearing techniques, such as those used in outdoor earthen ponds, struggle with inadequate water quality control and biosecurity. BFT offers a higher level of biosecurity and easier water quality management (Chim et al., 2014).

3..4 Cage and Pen Culture Innovations

Aquatic organisms are raised in cage or pen culture systems, which are enclosed structures set up in natural water bodies such as lakes, reservoirs, rivers, or coastal waters. While keeping the farmed organisms contained, these structures permit the free exchange of water with the surrounding environment (Shalom, 2001). Enclosing aquatic animals in net or mesh structures within natural water bodies, such as lakes, rivers, or oceans, is known as cage and pen culture. Creating strong cage systems that can withstand challenging open-ocean conditions, lessening the environmental impact on coastal areas, and gaining access to cleaner waters are some of the main areas of innovation in this industry. Nets and structures should be made of cutting-edge, long-lasting, and eco-friendly materials to stop escapes, lessen biofouling, and increase operational lifespan. Better protecting infrastructure and fish by designing cages that can be submerged during storms or to avoid surface problems (Shalom, 2001). Systems with controllable buoyancy are a notable aquaculture innovation, particularly for deep-water fish farming. A fish cage with one or more chambers that enable it to be submerged and refloat at a regulated rate to different depths is used in these systems. This ability is especially helpful for controlling environmental factors and shielding fish from unfavourable weather or surface disturbances (Shalom, 2001).

Fig.3: Cage and Pen Culture Innovations

3.5 Automated Feeding and Monitoring Systems
With the goal of enhancing mechanical automation in cultivation, the system was created to satisfy the industrialization and modernization requirements of pond aquaculture. Regardless of the culture system, automation is essential to aquaculture operations. These systems seek to increase animal welfare, decrease labour, and increase efficiency. Feeding fish according to their biomass, growth rates, water temperature, and oxygen content (WANG et al., n.d.). This lessens the impact on the environment, increases feed conversion ratios, and decreases waste. Employing sensors to continuously monitor vital indicators such as temperature, salinity, pH, ammonia, and dissolved oxygen. Wireless transmission of data to central control systems is common. Cameras are used to track fish health, growth, and behaviour in order to identify stress, illness, or less-than-ideal conditions early. Allowing operators to control systems and perform data analysis remotely, promoting timely decision-making and preventative maintenance (WANG et al., n.d.).

Fig.4: Automated Feeding and Monitoring Systems
Source: (Global Seafood Alliance)

3.6 Water Quality Management Tools
Several elements that serve as instruments for managing water quality are used in the aquaculture water quality monitoring system detailed in the paper: The Bottom-Layer Sensor is in charge of directly collecting different water quality parameters from the water. The monitoring data collected by the sensors is compiled and packaged by the Sensor Concentrator (Fu & Zhang, 2013). It makes data exchange with a host computer easier. The monitoring data is summarized and shown by the field's main machines. They have two options for uploading this data: wired and wireless. Additionally, the field's main machines provide an early-warning function and control signals to activate or deactivate the field water quality adjusting device(Fu & Zhang, 2013). Aquaculture water quality can be specifically adjusted with the Water Quality Adjusting Device. Data uploaded by the field main machines is gathered and stored by field-level monitoring centers, which then make it accessible to users for inquiries. They can also operate the devices that adjust the water quality (Fu & Zhang, 2013).

4. Sustainable Feed and Nutrition
The aquaculture sector is growing quickly, which means that sustainable protein sources must be developed to lessen dependency on conventional fish meal and oil, which have a limited supply and rising demand. Although they pose particular nutritional and processing difficulties, plant-based feedstuffs provide a good substitute (Gatlin et al., 2007). In order to solve environmental and financial issues, sustainable aquaculture is putting more and more emphasis on the creation of plant-based feeds and substitute protein sources. This change is necessary to lessen dependency on conventional fish oil and meal, which are unsustainable because of overfishing. Incorporating substitute ingredients like algae and insect meal improves feed conversion efficiency in addition to nutritional profiles (Gatlin et al., 2007).

4.1 Development of plant-based feeds
The most important oilseed crop in the world, soybeans (Glycine max Linnaeus), are used extensively in aquafeeds as soy protein isolate (SPI), soy protein concentrate (SPC), soy flour, and soy meal (SBM). With a high crude protein content and a relatively balanced amino acid profile, soybean products are both affordable and nutrient-dense (Gatlin et al., 2007). A number of antinutritional factors found in soybeans include oligosaccharides (raffinose and stachyose), which can impair nutrient digestibility and growth performance because fish lack α-galactosidases and are therefore largely indigestible (Gatlin et al., 2007). Although barley is cultivated for a variety of uses, including animal feed, its application in aquafeeds has been restricted due to its high fibre, low protein, β-glucans, and phytate content. Carnivorous fish value higher protein varieties, which have a protein content ranging from 9% to 15%. Barley bran contains β-glucans, which can have immunomodulatory effects, but prolonged feeding may be harmful (Gatlin et al., 2007).

4.2 Nutritional advancements and feed conversion efficiency
Reducing aquaculture's reliance on marine raw materials like fish oil (FO) and fish meal (FM) is imperative. Over 85% of the world's available FO and roughly 50% of its FM were predicted to be consumed by aquaculture by 2010. In order

to address the high rates of marine resource consumption, sustainable aquafeeds that use more terrestrial plant products must be developed (Bell & Waagbo, 2008). De-hulling and air classification are examples of pre-processing methods that can lower fibre and raise protein content. Yeast, bacterial, and fungal fermentations have the potential to remove antinutrients and add necessary nutrients through biological enhancement (Gatlin et al., 2007). The use of vegetable oils (VO) in place of fish oil (FO) in aquafeeds has advanced significantly. Diets containing 100% FO replacement by VO have proven effective for salmonids. Likewise, bream and bass fed diets containing up to 60% VO showed no adverse growth effects (Bell & Waagbo, 2008).

Furthermore, Fish oil and fish meal have long been the main components of aquafeeds. Their production worldwide, however, is not enough to support aquaculture's anticipated growth at the current rates of inclusion in feed formulations (Hardy, 2009). Due to this restriction, aquafeeds must increasingly contain alternative ingredients to supply substantial amounts of protein and energy. This presents opportunities as well as challenges for the industry and researchers. The main objective is to advance sustainable aquaculture, which calls for sustainable feeds that enable the fast, cost-effective growth of farmed fish and produce consumer-safe, healthful fisheries products (Hardy, 2009).

5. Disease Control and Health Management

A multifaceted strategy that incorporates different tactics to prevent and mitigate health issues in aquatic organisms is essential for effective disease control and health management in aquaculture. Probiotics and immunostimulants are important ways to boost fish's natural defences, but vaccination procedures and biosecurity measures are also important (Ganguly et al., 2010).

5.1 Vaccination practices

A key component of contemporary aquaculture health management is vaccination, which provides focused defence against particular pathogens. Vaccines provide future immunity by stimulating the fish's immune system to produce antibodies against inactivated or attenuated pathogens. This lessens the need for antibiotics and aids in halting the spread of disease (Ganguly et al., 2010). With its use spreading across a variety of fish species and microbial diseases in recent years, vaccination is a major factor in aquaculture disease prevention. For species like Atlantic salmon, rainbow trout, sea bass, sea bream, barramundi, tilapia, turbot, yellowtail, purplish and gold-striped amberjack, striped jack, and channel catfish, commercial vaccination is used (Håstein et al., 2005).

5.2 Probiotics and immunostimulants

Probiotics are substances or organisms that help the host animal's intestinal microbes maintain a healthier balance. Probiotics, when taken as dietary supplements, are generally successful in enhancing fish and crustacean growth, feed efficiency, and immunity (Ganguly et al., 2010). Immunostimulants are compounds, sometimes referred to as adjuvants, immunomodulators, or biological response modifiers, that are intended to boost the host's immune system. They can be taken as dietary supplements or as medications. Immunostimulants typically enhance immunity, feed efficiency, and growth performance in fish and crustaceans when added to diets, even in trace amounts (Ganguly et al., 2010). Immunostimulants and probiotics, even in small doses, when given as dietary supplements, generally enhance immunity, feed efficiency, and growth performance in fish and crustaceans (Ganguly et al., n.d.).

5.3 Biosecurity measures

A collection of procedures known as biosecurity is intended to stop the introduction and spread of illnesses both inside and between aquaculture facilities. Isolating new animals to make sure they are disease-free before reintroducing them to the main population is one of the most important biosecurity precautions. To get rid of infections, equipment, buildings, and cars should be cleaned and disinfected on a regular basis. Preserving ideal water conditions to lessen pathogen growth and fish stress. Avoiding crowding, which can cause stress and make people more prone to illness. Proper disposal of dead fish and other organic waste is needed to prevent pathogen spread, and stringent staff hygiene guidelines should be put in place to avoid cross-contamination (Ganguly et al., 2010).

6. Environmental Impact and Mitigation Strategies

In order to satisfy consumer demand for seafood, the aquaculture sector has grown dramatically, with marine shrimp farming seeing particularly rapid expansion (Browdy et al., 2001). However, this expansion has created environmental problems, mostly because intensive culture systems release nutrient-rich effluents that can cause receiving waters to become eutrophic. Numerous mitigation techniques have been created to address these problems, with an emphasis on waste management, effluent treatment, and careful site selection (Browdy et al., 2001). The growing severity of environmental regulations affecting the aquaculture industry prompted the launch of the AQUAETREAT project. The goal of this project is to discuss how production processes can adjust to stricter environmental regulations while also increasing productivity to stay viable (Mao et al., 2014).

6.1 Effluent treatment and reuse

Reusing and treating wastewater is essential for lowering the environmental impact of aquaculture operations, especially when it comes to treating discharge and minimizing water exchange. Water exchange in shrimp ponds can be drastically decreased or even eliminated, according to Browdy et al. (2001), scientific studies and industry experience. Compared to using water intake to raise dissolved oxygen levels, this method is more cost-effective and efficient. By filtering out particulate matter, sedimentation ponds can lessen the effects of effluents. Their effectiveness depends on factors like particle size, density, pond design, and effluent retention time (Browdy et al., 2001). It has been demonstrated that seaweed culture, employing species such as Ulva lactuca and Gracilaria sp., effectively eliminates high levels of dissolved ammonia and nitrate from aquaculture effluents.

Moreover, aquatic pollutants can be eliminated by wetland ecosystems using physical, chemical, and biological processes (Pérez, n.d.). A promising method for treating aquaculture effluents prior to discharge is constructed wetlands, or CWs (Pérez, n.d.). The low energy consumption, low operating costs, and low capital costs of this approach make it a popular choice for sustainable aquaculture methods. Organic matter must be removed by cutting and removing vascular vegetation to achieve mass conservation (Browdy et al., 2001). One important technique for treating aquaculture effluent is bioremediation. Through their metabolism, microorganisms, aquatic plants, or aquatic animals can absorb, assimilate, and break down organic and inorganic pollutants—including hazardous heavy metals—into innocuous compounds (Mao et al., 2014).

6.2 Waste management innovations

Common pollutants produced by aquaculture, including NH+4-N, NO−X-N, COD (Chemical Oxygen Demand), and SS (Suspended Solids), have been demonstrated to be effectively reduced by bioremediation. Usually, sediments, fish dung, biological waste, and excess bait are the sources of these contaminants (Mao et al., 2014). Materials left over after harvesting, mainly uneaten feed, excreta, chemicals, and therapeutants, are considered aquacultural wastes. Both sediments and farm effluents can be released from these wastes; sediments are collected sporadically, while effluents are released continuously (Ramírez-Godínez et al., 2013). Because of their high nutrient content, aquaculture effluents can be used for hydroponics and crop production as well as biological treatments like wetlands, biofilters, or algae-based systems.

Furthermore, for balanced microbial growth during biological treatment, exogenous carbon substrates may be required due to the high nitrogen-to-carbon ratio in aquaculture discharges (Ramírez-Godínez et al., 2013). The microbial community in the pond is essential to the dynamics of dissolved oxygen, the availability of natural food, and the recycling of nutrients. Techniques are emerging to manipulate this community through nutrient supplementation, habitat expansion, and the application of cultured microorganisms. Using carefully positioned drain ports, culture techniques have been developed to remove sludge during the growing season. Proper sludge removal can extract primarily organic material, reducing the impact of drain harvest effluent on receiving streams (Browdy et al., 2001).

6.3 Site selection and ecosystem protection

Protecting nearby ecosystems requires careful site selection and management techniques. One important factor in enhancing the long-term sustainability of marine shrimp farming is careful site selection. By doing this, places vulnerable to environmental deterioration are avoided (Browdy et al., 2001). Excessive freshwater use, the creation of organic-rich sediments, changes in water temperature and flow rates, and habitat alteration or destruction are all consequences of intensive aquaculture (Ramírez-Godínez et al., 2013). Additionally, it can change the biotic index, pollute water, and make it easier for infections to spread from farmed to wild animals (Ramírez-Godínez et al., 2013). Additional hazards include the introduction of exotic species, genetic hazards from escaped culture animals, the development of antibiotic resistance, and the decline in the wild fish population for the purpose of raising carnivorous species.

Eutrophication and excessive organic enrichment of estuarine waters can result from the discharge of nutrient-rich effluent, which lowers farm productivity and puts more stress on the target crop (Browdy et al., 2001). The goal of mitigation techniques is to stop these effects. There are a number of benefits to raising bivalves (like oysters) with shrimp because they help to improve the quality of the water by filtering suspended solids and algae. Additionally, they can share production inputs and function as a valuable secondary crop (Browdy et al., 2001). For farmed fish, maintaining ideal water quality is essential; important factors include dissolved oxygen, pH, ammonia, and nitrites (Ramírez-Godínez et al., 2013). In order to address issues ranging from effluent discharge to the wider ecological footprint, sustainable aquaculture practices require proper waste management and careful consideration of water quality parameters.

7. Policy, Governance, and Certification Schemes

Aquaculture certifications have played a crucial role in forming national and international governance and regulatory frameworks. Certifications such as GlobalG.A.P. and the Aquaculture Stewardship Council (ASC) have become vital resources for advancing sustainable practices, improving product traceability, and guaranteeing adherence to social and environmental norms. These frameworks have greatly impacted community-based aquaculture practices. In order to ensure the sustainable and orderly growth of the industry, aquaculture governance includes community-based practices, certifications, and international and national regulatory frameworks (Hishamunda et al., 2013).

7.1 Global and national regulatory frameworks

Governments are essential to the administration and regulation of aquaculture, including the creation of policy instruments, strategic planning, and licensing processes. Determining national aquaculture development laws, policies, plans, and strategies is part of this (Hishamunda et al., 2013). The FAO Code of Conduct for Responsible Fisheries (CCRF), especially Article 9, and FAO-published guidelines for lowering administrative burdens and enhancing aquaculture planning and policy development are used by many governments around the world (Hishamunda et al., 2013). To meet food security and economic development goals sustainably without degrading the environment, aquaculture growth management requires a new strategy. This suggests that new or updated national and international regulatory frameworks are required (Brummett, 2013). Aquaculture zone management that is tailored to the local environment is suggested as a way to reduce investment and environmental risks. This points to a decentralized, situation-specific method of governance (Brummett, 2013).

7.2 Role of certifications

The objectives of these certification programs are in line with the idea of best management practices (BMPs) and farming technique manuals that trade associations and development organizations promote (Hishamunda et al., 2013). These programs seek to promote responsible behaviour and guarantee the sector develops in an orderly and sustainable manner. In order to reduce negative externalities and balance private interests with societal objectives, the text highlights the necessity of limiting the behaviour of entrepreneurs, ideally through self-regulation or financial incentives. This implies that standards are required, which certifications can assist in enforcing (Hishamunda et al., 2013).

7.3 Community-based aquaculture practices

When establishing goals for employment and conservation in aquaculture development, the priorities of the local communities should serve as a guide (Brummett, 2013). Assessing a variety of ecosystem services that show ecosystem health and, most importantly, taking into account the preferences of knowledgeable local communities should help determine the acceptable level of impacts from aquaculture. This emphasizes how crucial local knowledge and community involvement are to sustainable aquaculture management (Brummett, 2013).

8. Case Studies on Successful Sustainable Aquaculture Models

i. Integrated Agriculture-Aquaculture Project in Western Cape

Salie et al. (1998) describe the thorough analysis of a Western Cape, South Africa, integrated agriculture-aquaculture project, which revealed a viable, sustainable aquaculture model that can be implemented in existing irrigation water bodies. The project demonstrated that the aquaculture activity had no adverse effects on the parameters of water quality, such as conductivity, turbidity, pH, nitrogen, or the amount of total dissolved and suspended solids. This is important because high-value crops like table grapes and export-destined deciduous fruits are the main crops that are irrigated by the water bodies. Using a cage system, the aquaculture project produced 4,500 kg of trout over a seven-month growth period. This endeavour yielded a noteworthy 17.2% return on investment. Without putting undue strain on water consumption, the model makes use of existing irrigation dams, which are common in areas like the Western Cape (more than 2,000 dams with volumes exceeding 500,000 m^3), for aquaculture. An estimated 5,800 tons of freshwater fish could be produced annually by such dams. Through the demonstration of positive economic returns without compromising water quality necessary for other primary uses, this case study demonstrates that aquaculture can be sustainably integrated with agricultural practices, especially in regions with existing water infrastructure.

9. Challenges and Limitations

Despite its potential to improve economic growth and food security, aquaculture has a number of serious drawbacks. These can be broadly divided into three categories: research and development gaps, economic and sociopolitical constraints, and technological barriers. Disease outbreaks can spread quickly and result in considerable financial losses in intensive aquaculture systems. It is still challenging to create disease-resistant strains, biosecurity measures, and effective vaccines (Stricker et al., 2009). With some exceptions, such as contemporary cages and specific aerators and feeding systems, the aquaculture sector currently shows a startling lack of equipment standardization (Børresen, 2010).

Waste products from aquaculture operations, such as uneaten feed and feces, can contaminate nearby waters. The development of sustainable technologies for integrated multi-trophic aquaculture (IMTA), recirculation aquaculture systems (RAS), and waste treatment is hampered by their complexity and high cost (Stricker et al., 2009). Technologies from other fields, like marine engineering, are frequently appropriated. Although reusing water and lowering emissions make systems like Recirculation Aquaculture Systems (RAS) better for the environment, they are expensive to buy and run (Børresen, 2010). Additionally, these systems require specialized medical care, close supervision, and a high level of expertise. Wild fish stocks are under stress because many carnivorous farmed fish depend on fishmeal and fish oil from wild fish. One ongoing technological challenge is creating affordable, sustainable substitute feed ingredients (such as plant-based proteins, insect meal, and algae meal) (Stricker et al., 2009). Even though there are selective breeding programs in place, more technological developments are required to speed up genetic improvement for characteristics like disease resistance, growth rate, and feed conversion efficiency in a larger variety of aquaculture species (Stricker et al., 2009).

Access to markets, price swings, and competition from wild-caught fisheries are some of the issues that aquaculture producers frequently deal with. It is essential to establish robust market demand and stable supply chains (Stricker et al., 2009). Aquaculture development can be hampered by complicated and regionally disparate regulations, especially for new species or technologies. The permitting process can be expensive and time-consuming (Stricker et al., 2009). The industry is subject to market and economic risks, such as changes in consumer preferences and fluctuations in input and product prices (Børresen, 2010). Political risks also impact the legal framework for trade and production. Aquaculture faces competition from other industries for land and water resources. Other resource users may also have an impact on and influence its operations (Børresen, 2010).

In light of concerns about food safety, animal welfare, and the environment, aquaculture may not be seen favorably by the general public. Addressing community issues and obtaining social license to operate are essential for growth. A major obstacle to starting aquaculture farms can be the high initial capital expenditure, particularly for sophisticated systems. There is frequently limited access to financing and insurance specifically designed for the aquaculture industry (Stricker et al., 2009). Aquaculture development can be hampered rather than helped by inadequate administrative and regulatory frameworks. Regulation of resource access and environmental guidelines are among the issues. The efficiency of the license/permit allocation system, particularly regarding timeliness, complexity, duration, and renewal, poses a 'political' risk for investors (Børresen, 2010).

Regardless of their demonstrated technical viability in Asia, the rapid growth of sophisticated systems like IMTA (Integrated Multi-Trophic Aquaculture) is hampered by social acceptance in many regions of the world (Børresen, 2010). Aquaculture is still not well known to consumers, and there are unfavourable opinions about the use of fishmeal and oil, hormones, medications, and the effects on the environment. Because of worries about food safety, animal welfare, and the environment, aquaculture may not be seen favorably by the general public. Addressing community issues and obtaining social license to operate are essential for growth (Stricker et al., 2009).

In areas like better water use, selective breeding, and feed formulation, adaptive innovation must be supported, and producers' better/best practices must be acknowledged and encouraged. To manage escapes, disease, pollution, and other environmental externalities as effectively as possible, research and development are required. The growth of aquaculture is hindered by a number of factors, including high-cost technologies, ineffective regulations, competition for resources, and the need for more public acceptance and policy coherence, despite the fact that aquaculture has great potential for food security. To guarantee a sustainable and prosperous future for the industry, addressing these complex issues calls for coordinated efforts in innovation, governance, and communication.

Conclusion

One of the industries with the fastest rates of growth in food production is aquaculture, which is essential to food security, economic expansion, and global nutrition. Traditional methods have gradually given way to sophisticated, technologically driven systems like Biofloc technology, Integrated Multi-Trophic Aquaculture (IMTA), and Recirculating Aquaculture Systems (RAS). Through increased biosecurity, waste reduction, and water efficiency, these innovations have made a substantial contribution to sustainability. In order to address ecological concerns, feed formulation advancements have further decreased reliance on fishmeal and fish oil by utilizing plant-based and alternative protein sources. Probiotics, vaccines, and biosecurity procedures are examples of health management techniques that have reduced disease outbreaks and improved animal welfare and productivity.

Notwithstanding these successes, difficulties still exist. High operating costs, a lack of adoption by small-scale farmers, environmental hazards, and uneven regulatory enforcement still hamper the widespread adoption of sustainable practices. Fostering accessible innovations, improving genetic improvement initiatives, fortifying legislative frameworks, and advancing international certification programs that support ethical aquaculture are all essential to future advancement. In conclusion, aquaculture has much potential to help the world's resource-constrained population meet its growing protein needs. Aquaculture has the potential to develop into a resilient, sustainable, and socially conscious food production system with continued innovation, improved governance, and inclusive community involvement.

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