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The Future of Aquaculture: Sustainable Development, Economic Growth, and Environmental Protection

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Abstract Aquaculture is one of the fastest-growing food production sectors globally, playing a vital role in food security, employment, and economic development. This review synthesizes literature spanning from 1988 to 2024, with a primary focus on contemporary advancements and policy shifts within the last decade, to evaluate the balance between seafood demand and ecosystem integrity. While it supports millions of livelihoods, ensuring sustainability remains a challenge. The study identifies that traditional intensive systems have caused groundwater salinization, mangrove loss, and chemical residue accumulation. Modern aquaculture utilizes diverse species-seaweeds, mollusks, and finfish to promote resource optimization. With the decline in capture fisheries, many nations have shifted toward inland and integrated farming systems. Sustainable development now emphasizes ecosystem-based management, including wetland conservation, effective effluent treatment, and biodiversity protection. Strengthening biosecurity, disease surveillance, and reduced antibiotic use are essential for meeting global hygiene standards. In tropical regions, integrated models like rice-fish culture are evolving into advanced systems such as Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and Biofloc Technology (BFT). These innovations aim to minimize footprints while improving resource efficiency and biological balance. Overall, promoting environmentally responsible and socially inclusive aquaculture is crucial for conserving marine ecosystems and safeguarding the future of global seafood security.
Keywords Sustainable aquaculture; Integrated farming; IMTA and livestock farming; Organic aquaculture

1 Introduction

Aquaculture plays a vital role in ensuring global food security and enhancing the livelihoods of small-scale and marginal fish farmers. Currently, the oceans cover approximately 70% of the Earth's surface, hosting biological communities ranging from microscopic prokaryotes to the mammoth blue whale. These marine ecosystems provide essential services and food products; however, they are increasingly threatened by ocean acidification, rising sea surface temperatures, marine litter, and coastal pollution. Furthermore, these ecosystems remain relatively under-explored, offering significant potential for the discovery of novel bioactive molecules and secondary metabolites.

The fisheries sector is multifaceted, encompassing capture, commercial, artisanal, and recreational fishing, alongside freshwater and marine aquaculture. Notably, aquaculture has overtaken capture fisheries as the primary source of seafood for human consumption, serving as a vital alternative to mitigate food security challenges and prevent the depletion of wild fish stocks (White and Lopez, 2017). Global production has escalated from 19 million tons in 1950 to 122 million tons in 2020 (FAO, 2022a). Sustainable management is essential to strengthen the resilience of coastal ecosystems and achieve the United Nations Sustainable Development Goal (SDG-14), which emphasizes the conservation and equitable use of oceanic resources by 2030.

Developing sustainable "incubator systems" in maritime nations can foster environmentally conscious businesses and ensure equitable economic growth (OECD/World Bank, 2016). However, the scientific community recognizes that the intensive use of land and water, chemical eco toxicity, and the introduction of non-native species are major drivers of biodiversity loss (Peay et al., 2019). Historical intensification of shrimp farming, for instance, has been linked to soil salinization, reduced agricultural yields, and the degradation of mangrove wetlands.

Ensuring environmental protection at an acceptable level is mandatory given the rising global food demand. Transitioning toward resource-efficient and technologically advanced systems-such as Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and well-managed offshore cage farming-can address the challenges associated with conventional methods (Brugere and Ridler, 2004). Ultimately, the effective protection of the marine environment supports the creation of high-value products, including new pharmaceuticals, renewable energy, and sustainable protein sources.

2 Methods Adopted

This review was conducted using a systematic literature search strategy to ensure rigor, transparency, and relevance. Scientific databases including Scopus, Web of Science, PubMed, Science Direct, and Google Scholar were searched to collect peer-reviewed literature related to sustainable aquaculture practices in India and globally. The time window for literature selection covered publications from 1988 to 2024, with greater emphasis on studies published after 2010 to ensure contemporary relevance.

The primary keywords used for the search included: sustainable aquaculture, biosecurity in aquaculture, integrated multi-trophic aquaculture, recirculatory aquaculture systems, shrimp farming sustainability, climate change and aquaculture, inland fisheries management, and biodiversity conservation in aquaculture. Boolean operators (AND, OR) were applied to refine search combinations and improve specificity.

Inclusion criteria comprised peer-reviewed journal articles, review papers, official reports (e.g., FAO and national fisheries agencies), and research studies directly addressing sustainability, ecological management, disease control, productivity enhancement, and environmental impacts in freshwater, brackishwater, and marine aquaculture systems. Exclusion criteria involved non-scientific opinion articles, duplicated studies, papers lacking methodological clarity, and publications not directly related to aquaculture sustainability.

The selected studies were screened initially based on title and abstract relevance, followed by full-text evaluation for methodological robustness and data reliability. Extracted data were categorized into thematic areas including ecological aspects, natural resource management, biodiversity conservation, biosecurity, climate resilience, and socio-economic sustainability. A qualitative descriptive synthesis approach was adopted to compare findings, identify common trends, highlight gaps, and draw integrative conclusions regarding sustainable aquaculture development. This structured methodology ensures that the review is comprehensive, evidence-based, and aligned with contemporary academic standards for systematic review articles.

3 Sustainable Aquaculture Production

3.1 Overview of sustainable aquaculture

Sustainable aquaculture systems are engineered to maximize socio-economic benefits while mitigating adverse environmental impacts. Despite economic fluctuations, aquaculture remains a cornerstone of rural livelihoods and food security, particularly in Indian states like Andhra Pradesh. In regions such as West Godavari, the sector has transitioned into high-density farming zones. However, the intensification of commercial practices-including integrated rice-fish farming-faces challenges regarding long-term ecological resilience. Transitioning toward moderate stocking densities and optimized feed application is essential to satisfy international market demands while maintaining ecosystem health (Betala and Betala, 2025).

3.2 Traditional aquaculture systems and their challenges

In Southeast Asia, traditional systems like rice-cum-fish and carp polyculture are being refined through Environmental Impact Assessments (EIA) to eliminate the misuse of aqua chemicals and promote natural resource conservation. Sustainability in these systems is achieved by managing biomass and waste through strategic site selection and the determination of carrying capacity (Wurts, 2000). Comprehensive hazard assessments are vital to prevent disease transmission and ensure food safety for human consumption.

3.3 Environmental challenges in aquaculture

A significant environmental challenge is the discharge of aquaculture effluents, which contain dissolved nutrients like nitrogen that contribute to eutrophication, particularly in cage culture systems. High-density culture environments can stress aquatic species, increasing susceptibility to disease and leading to a reliance on antibiotics, which further deteriorates water quality (Noor et al., 2019). Furthermore, the transition from traditional rotational cropping to intensify shrimp culture has occasionally resulted in poor water quality and reduced growth rates. A critical ecological risk is the escape of farmed fish, as interbreeding with wild populations can lead to high mortality rates and reduced genetic fitness in offspring.

3.4 Freshwater aquaculture in India

Freshwater aquaculture development in India continues to expand, though it faces constraints related to input availability and environmental management (Jayasankar, 2018). Cage aquaculture has been introduced as a viable method for ecosystem-based management, showing success with species such as cyprinids, perches, and catfishes (Radhakrishnan et al., 2010). When managed correctly, these systems leverage natural productivity (phytoplankton and zooplankton) to provide economic opportunities for rural communities. Currently, India is the second-largest fish producer globally, contributing approximately 8% of total production. The country continues to leverage its vast inland resources-including rivers, reservoirs, and tanks through strategic development programs aimed at enhancing sustainable productivity (Table 1, Table 2).

Table 1 Marine resources and statistics

Parameter	Value	Unit	Source
Total Coastline Length	8,118	km	Government of India / FAO (2022-2024)
Exclusive Economic Zone (EEZ)	2.02	million km²	FAO (2022-2024)
Continental Shelf Area	0.42	million km²	FAO (2022-2024)
Fish Landing Centers	1,376	Number	National Marine Fisheries Census (2005)
Fishing Villages	3,322	Number	National Marine Fisheries Census (2005)
Fishermen Families	764,868	Number	National Marine Fisheries Census (2005)
Total Fisher folk Population	3,574,704	Number	National Marine Fisheries Census (2005)

Table 2 Inland resources

Parameter	Value	Unit
Rivers and Canals	195,210	km
Reservoirs	3.15	million hectares
Tanks and Ponds	2.414	million hectares
Flood Plains / Derelict Water Bodies	0.8-1.2	million hectares
Brackishwater Area	1.24	million hectares
Saline / Alkaline Affected Area	1.20	million hectares

3.5 Brackish water aquaculture in India

India has contributed remarkable aquaculture producer, contributing significantly to both domestic and international markets. The country leverages vast inland resources like ponds and tanks, along with brackish/saline areas, for a variety of fish like carps, catfish, and tilapia, and has expanded into saline water aquaculture using inland saline groundwater. This is exemplified by the commercial farming of the Pacific white leg shrimp (*Litopenaeus vannamei*) in states like Haryana, Punjab, Rajasthan, and Uttar Pradesh. India is the second-largest producer of aquaculture in the world. The emphasis on brackishwater aquaculture invited large number of private companies and multi-nationals in intensive aquaculture resulted detrimental impact and serious environmental and health issues among the coastal community due to large conversion of thousands of hectares of coastal lands for intensive shrimp farming. The mangroves were cleared, wetlands were encroached and drained, and aquaculture tanks were built into freshwater lakes. Apart from saltwater intrusion into freshwater bodies, including aquifers, and aquaculture practices led to the release of contaminants into water sources.

3.6 Intensification vs sustainability in aquaculture

In India, over 1.4 billion people are significantly affected by environmental issues arising from agricultural intensification, which impacts both terrestrial and aquatic ecosystems. Inland aquatic resources have declined over recent decades due to landscape destruction, water pollution, and the over-exploitation of fish stocks, leading to a marked depletion in biodiversity. Intensive aquaculture contributes to this lack of sustainability through nutrient enrichment, soil leaching, and groundwater salinization. A critical concern is the widespread use of antibacterial medicines; the discharge of antibiotics into the environment-often via wastewater-facilitates the development of selective drug resistance in bacteria. Exposure to sub-lethal levels of these compounds allows bacteria to evolve resistance, making future infections increasingly difficult to treat with standard clinical medicines (Pillay, 1994).

Marine pollution, driven by eutrophication and the sedimentation of organic matter, acts as a significant pollutant source, causing harmful environmental impacts as large amounts of nutrients sink to the benthos (Dawood and Koshio, 2020). Intensification results in habitat destruction and compromised water quality due to the accumulation of metabolic waste and uneaten feed, which ultimately stresses the cultured organisms. The environmental footprint varies across systems; extensive systems have minimal impact, whereas intensive operations generate substantial waste depending on stocking density, feed inputs, and waste treatment efficiency (Maulu et al., 2021). Common detrimental practices include the release of dissolved nutrients, feces, and carcasses into water bodies containing aquaculture cages. Consequently, pathogens such as *Aeromonas salmonicida*, *Vibrio* sp., and motile aeromonads have developed significant resistance. Furthermore, fish larvae and fingerlings are highly vulnerable to pesticides and heavy metal pollution, which primarily damage the gill, kidney, and liver tissues (De Kinkelin and Michel, 1992).

Globally, sustainable aquaculture has become a revitalizing economic force for rural communities. To achieve long-term viability, there is an increasing emphasis on eco-labeling and the adoption of ecosystem-based approaches (FAO 2009a, b; Davenport et al., 2018). While some chemicals used in aquaculture, such as certain parasiticides, break down quickly, others like organotin and antibiotics-including oxytetracycline and flumequine-can significantly alter bacterial ecology and sedimentation processes (Shah et al., 2018). The residual effects of hormones used for induced spawning and growth stimulation also pose potential health hazards to humans. Ecologically, the most severe impacts include the loss of biodiversity and the destruction of mangroves, which serve as vital breeding grounds. Globally, shrimp pond construction has led to the loss of approximately 3.7 million acres of mangroves; in some Asian nations, this accounts for 27% to 50% of total mangrove area (Pillay, 1994). In contrast, the removal of mangroves for shrimp farming is less common in India, where strategies focus on integrated and responsible farming practices to address sustainability (Ninawe, 1999).

4 Risks/ Hazards in Aquaculture

4.1 Issues and concerns

Aquaculture plays a critical role in global food production, and its sustainable development is a key focus for international bodies like the United Nations (UN) and the Food and Agriculture Organization (FAO). The concept of sustainability, as defined by the World Commission on Environment and Development (WCED), emphasizes meeting current needs without compromising the ability of future generations to meet their own. This necessitates adopting practices that ensure long-term productivity, minimize environmental impacts-such as waste and pollution-and contribute to economic growth across related sectors like agriculture and forestry. Historically, the FAO has recognized that responsible management is essential for securing future food supplies and maintaining healthy ecosystems. FAO declarations provide the foundation for policies aimed at ensuring the long-term viability of aquatic food systems by minimizing waste and pollution in adherence with the broader sectors of agriculture, fisheries, and forestry (FAO, 1988).

Risk analysis in aquaculture involves identifying potential hazards with the capacity to cause economic loss or introduce harmful pathogens into the aquatic environment, which impacts genetic diversity, ecological integrity, and food safety. These hazards can have a broad impact on the environment and human health, often leading to significant, long-lasting damage. Natural disasters-such as tsunamis, floods, and wildfires-can destroy habitats and alter ecosystem functions. Additionally, industrial accidents, oil spills, or chemical leaks introduce toxins into the air, water, and soil, while prolonged droughts deplete water resources, impacting both agriculture and natural water bodies (Hader et al., 2020; Cramer et al., 2018; Harun et al., 2021). Specific aquaculture uncertainties include harmful algal blooms (HABs), which produce toxins that affect aquatic organisms and pose significant public health risks through the food chain. Silt buildup, poor water quality, and fish escapes are also recognized as major challenges (Bondad-Reantaso et al., 2018; Luna et al., 2020). These risks involve genetic issues, climate change, habitat structural changes, and occupational hazards (Yang et al., 2020).

In closed aquaculture technologies, water quality is maintained with minimal exchange with natural waterways, reducing pollution, negative wildlife interactions, and the transfer of parasites or diseases. Improving aquaculture performance is essential to provide safe, nutritious food while minimizing the environmental footprint. This ecologically friendly approach increases production efficiency relative to the land, water, feed, and energy used (Richard Waite, 2014). India promotes carp polyculture as a sustainable production method based on ecological principles that maximize resource utilization. By stocking compatible species-including surface feeders, column feeders, bottom feeders, and plankton feeders-all available ecological niches within the pond are utilized efficiently. This ecological basis for sustainability is further enhanced by waste recycling and resource management through modern engineering approaches (Jana et al., 2000; Jana, 2003). Conversely, the destruction of mangrove swamps-which are ecologically sensitive nurseries-directly impacts coastal estuaries, fish migration, coral reefs, and seagrass beds, ultimately affecting marine biodiversity and the livelihoods of coastal communities.

4.2 Climate change and fisheries

Climate change significantly impacts aquaculture production through fluctuations in water temperature, sea-level rise, and increased disease prevalence. Implementing robust mitigation techniques and adaptation strategies is essential to address extreme climate variance, overcome severe disruptions, and adapt to evolving ecosystem dynamics for sustainable development (Shukla et al., 2019; Galapaththi et al., 2020). Developing climate resilience strategies-such as the adoption of Biofloc Technology (BFT) and Recirculating Aquaculture Systems (RAS) assists farmers and stakeholders in withstanding adverse environmental shifts. Furthermore, Integrated Multi-Trophic Aquaculture (IMTA), cage culture, monosex tilapia farming, and the cultivation of air-breathing fishes serve as critical components of climate-smart aquaculture. These management strategies resist environmental changes by combining mitigation and adaptation to protect threatened marine ecosystems and fisheries.

According to the United Nations Conference on Trade and Development (UNCTAD), global fishing fleets powered by fossil fuels, such as marine diesel, emit between 0.1% and 0.5% of global carbon emissions, totaling up to 159 million tons annually. Consequently, understanding the impact of climate change on fisheries management is vital for developing policies that emphasize practical water quality management. This includes regular monitoring of critical parameters such as pH, ammonia, and dissolved oxygen levels-and the implementation of efficient water circulation systems. Utilizing bio-filters to remove waste products and excess nutrients is essential for maintaining optimal water quality and reducing the overall environmental footprint of aquaculture operations in a changing climate.

4.3 Carrying capacity and production

Carrying capacity refers to the maximum population density of a species that a given environment can support indefinitely without causing irreversible damage to the ecosystem or the health of the cultured stock. This threshold ensures productivity can be sustained without deleterious effects on the surrounding aquatic environment (Chapman and Byron, 2018). Carrying capacity is evaluated throughout the site selection procedure, beginning with initial capability calculations and receiving particular emphasis during the establishment of aquaculture facilities. This process adheres to spatial and temporal dimensions by evaluating the complete range of available space before determining suitable locations (Weitzman and Filgueira, 2020).

Furthermore, carrying capacity encompasses a cultural dimension; it is a dynamic process dependent on evolving standards and innovative concepts designed to avoid ecological overreach. Emphasizing community satisfaction and economic benefits is essential, particularly through the implementation of eco-friendly technologies. Consequently, long-term sustainability is realized when community needs are met through sufficient economic rewards derived from green technologies that provide additional resource benefits (Van Senten, 2018; McQuatters et al., 2019)

4.4 Health and disease management

Vaccination and rigorous biosecurity protocols are fundamental pillars of modern aquaculture, essential for the prevention and mitigation of disease outbreaks. Enhanced health management practices, supported by rapid detection and timely response systems, minimize economic losses and curtail the excessive use of antibiotics, thereby addressing the global challenge of antimicrobial resistance (FAO, 2022b; WOAH, 2023). Intensive aquaculture, particularly shrimp farming, has historically faced environmental degradation and disease crises, necessitating regulatory interventions to ensure long-term viability. In India, the native tiger shrimp (*Penaeus monodon*) industry suffered catastrophic losses due to viral pathogens, notably the White Spot Syndrome Virus (WSSV). In response, the exotic whiteleg shrimp (*Litopenaeus vannamei*) was introduced following comprehensive risk assessments and officially permitted for commercial culture in 2009. This transition significantly bolstered productivity and biosecurity management while enhancing economic returns and addressing socio-economic concerns (FAO, 2022a; Government of India Fisheries Reports, 2023).

Sustainable shrimp aquaculture has increasingly expanded into inland saline environments, such as Haryana, where eco-friendly technologies and community-based models have demonstrated environmental compatibility and improved rural livelihoods (Raghunathan et al., 2024). Achieving ecological sustainability requires scientific site selection, biosecure hatchery designs, effective effluent management, and optimized feed formulations. Furthermore, climate change poses significant risks to both freshwater and coastal systems through thermal stress, extreme weather events, and salinity fluctuations, which exacerbate disease susceptibility (FAO, 2023; IPCC, 2022). Consequently, strengthening policy frameworks and implementing climate-resilient farming strategies are critical for maintaining environmental monitoring and ensuring global seafood security

5 Fishing Regulations in India

In India, fishing is regulated within territorial waters and the Exclusive Economic Zone (EEZ); specifically, the zone within 12 nautical miles of the coast falls under the 'State List' of the Constitution. Coastal states and Union Territories (UTs) manage these activities through the Marine Fishing Regulation Act (MFRA). Modern aquaculture supports these frameworks by implementing rigorous biosecurity and disease control systems, minimizing the use of antibiotics and pharmaceuticals, and ensuring microbial sanitation. These practices maintain global hygiene standards while optimizing transport, traceability, and profitability. Furthermore, established aquaculture zones promote farm well-being by defining clear responsibilities for aquaculturists, fostering community involvement, and ensuring worker safety with equitable compensation.

To address historical ecological drawbacks, the Government of India introduced the National Policy on Marine Fisheries (NPMF) to prioritize the long-term sustainability and conservation of marine fishery resources. Key conservation measures include sea ranching, the installation of artificial reefs, and the farming of mussels, clams, and seaweed, alongside integrated cage farming systems. These efforts are central to the 'Blue Economy Growth Initiative,' which focuses on the sustainable utilization of aquatic wealth to improve the livelihoods of fishermen and their families (NPMF, 2017). By aligning resource management with economic development, the initiative seeks to realize the full potential of marine resources while safeguarding biodiversity for future generations.

6 Coastal Zone Regulations and AAI

The Coastal Regulation Zone (CRZ) Notification of 1991, enacted under the Environment (Protection) Act of 1986, imposes strict prohibitions on the expansion of industrial operations within ecologically sensitive coastal zones. Legal interventions have directed Union and State governments to discontinue intensive prawn farming in fragile areas, instead prioritizing regulated hatcheries and the introduction of *L. vannamei* and Specific Pathogen Free (SPF) *Penaeus monodon* for sustainable production. Shrimp farming in India has experienced cycles of rapid growth followed by setbacks, notably the disease epidemics of the late 1990s. Transitioning from the native black tiger shrimp to the exotic Pacific white shrimp (*L. vannamei*) has since revitalized the sector, contributing significantly to seafood exports and coastal livelihoods. Manoj and Vasudevan (2009) emphasize that robust regulatory mechanisms are essential to address environmental challenges such as nutrient enrichment, salinization, and mangrove destruction. To provide a formal legal framework, the Coastal Aquaculture Authority (CAA) was established in 2005 to ensure that activities are conducted in an eco-friendly manner.

Mandatory CAA guidelines now require Effluent Treatment Systems (ETS) for farms exceeding 5 hectares within the CRZ and 10 hectares outside the CRZ to mitigate adverse ecological impacts on open waters. Historically, the influx of private and multinational companies in the 1990s transformed traditional practices into intensive systems, often at the expense of mangrove ecosystems. Mangroves are vital for coastal food security, providing breeding grounds for crabs, prawns, and finfish, while also protecting groundwater aquifers from saline intrusion and buffering against tsunamis and floods. Globally, the rapid expansion of aquaculture has raised sustainability concerns, as unlimited profit motives and poor pond management have led to litigation and social conflict. In countries like the Philippines, Indonesia, and Thailand, high rates of mangrove depletion are directly attributed to shrimp farming expansion.

India accounts for approximately 3.3% of global mangrove cover, with significant areas located in West Bengal, Gujarat, and the Andaman and Nicobar Islands. Historically, some of these wetlands were drained for aquaculture tanks, leading to salt-water intrusion and the release of contaminants into local aquifers. Globally, such environmental degradation negatively impacts genetic diversity, water quality, and the overall feasibility of culture systems (Nesar Ahmed and Marion Glaser, 2016). To ensure long-term sustainability, integrated models combining agriculture, aquaculture, and salt panning are being promoted to meet the diverse dietary and livelihood requirements of coastal communities (Salin and Ataguba, 2018). These integrated approaches aim to harmonize economic development with the preservation of critical coastal habitats.

7 Promotion of inland aquaculture

In freshwater systems, the sustainability of a species depends on its ability to breed in captivity, optimize nutrient output, and adapt to resource-efficient culture environments. Polyculture is generally preferred over monoculture to meet the rising demand for animal protein by maximizing productivity per unit area. As the world's fastest-growing food-producing sector with an annual growth rate of 8.0%, aquaculture in India relies heavily on bulk production of Indian Major Carps (IMC), namely *C. catla*, *L. rohita*, and *C. mrigala*. Additionally, exotic carps such as *H. molitrix*, *C. idella*, and *C. carpio* constitute the second most significant group of cultured fishes. This six-species combination is a cornerstone of modern polyculture in South Asia, achieving high yields by utilizing all ecological niches: the surface (*C. catla* and *H. molitrix*), column (*L. rohita* and *C. idella*), and bottom (*C. mrigala* and *C. carpio*).

Major carps (IMCs) account for approximately 80% of total production in these systems, while exotic species like silver, grass, and common carp contribute significantly to maximizing spatial and nutritional efficiency (Laxmi Prasad et al., 2020). The adoption of such advanced polyculture systems-including sewage-fed aquaculture-enhances food security, builds resilience against extreme weather, and supports the livelihoods of rural farmers (Ghosh, 2020; Bhattacharya, 2021). Despite this potential, challenges such as low technology adoption, disease prevalence, and the high cost of quality feed must be addressed through scaled-up dissemination and capacity building (Lakra and Gopalakrishnan, 2021). Furthermore, biotechnological advancements, including the use of synthetic hormones for breeding, monosex culture, polyploidy, and transgenesis, are revolutionizing the industry. These modern approaches improve nutrition, health management, and gene banking, ultimately bolstering the global aquaculture sector (Lakra and Ayyappan, 2003).

8 Human Resource Development

Currently, India requires technically skilled fisheries professionals to navigate future industry challenges. Enhanced education is vital for improving fish productivity and generating employment across academic institutions, industrial research facilities, and state government departments (Kamleshbhai et al., 2024). Despite ongoing efforts to strengthen manpower, a significant shortage remains in this rapidly growing sector, which ultimately constrains overall growth. Fisheries education fosters innovation and creates employment by transferring specialized knowledge to farmers and stakeholders. Because the sector is highly skill-based, professional training is essential for equipping the workforce for roles in resource management and industrial operations. While comprehensive data are limited, an increasing number of universities now offer advanced M.Sc. and Ph.D. programs in aquaculture and marine sciences to address these needs.

In many higher education programs, modern communication technologies are being effectively utilized to disseminate technological expertise. Graduates with hands-on field experience are better prepared to manage commercial farms and address the technical challenges facing the aquaculture industry. Extension programs further support sector growth by transferring best practices to practitioners, while specialized training-such as scuba diving for resource assessment-addresses critical human resource gaps in deep-sea fishing and governmental departments. Furthermore, the Central Institute of Fisheries Education (CIFE), through its HRD initiatives, has trained a significant number of extension workers who promote sustainable practices nationwide. These trained professionals find diverse employment in research, academia, and administration, where their expertise helps build robust cold chains and marketing networks to reduce spoilage and waste.

9 Sustainable Ecofriendly Aqua Farming Technologies

The integrated fish farming (IFF) is an optional solution refers to the production and integrated management of comprehensive use of aquaculture, agriculture and livestock giving emphasis on a sustainable farming system. It is efficiency better in resources utilization in enhanced income and higher food fish production. IFF is simple, cost-effective technology to ensure employment, food and nutritional security for marginal and small hill farmers suitable to use resources sustainably to achieve the productivity as economic viable systems. It enhances the net return, generates employment, conserves natural resources, reduces the cost of production and increases the income by minimizing risk enable farmers producing diverse food by conserving resources well. IFF practices are highly eco-friendly and ensures higher returns as well as suitable for sustained production of fish and other components (Deepa Bisht, and Harshit Pant Jungran, 2023). The practice of carp polyculture introduced in China and India, as a traditional aquaculture production technique and in many Asian nations with integration of conventional management practices of animal husbandry. The farming supports aquaculture as ecologically healthy ecosystem with culture of native carp species, freshwater prawns with appropriate stocking of different fishes having different feeding habits. The wastage generated from agriculture also utilizes as fertilizer or feed in fish culture. Thus fishery sector plays a vital role in the socio- economic development of the state and is recognized to stimulate the growth of several subsidiary industries and is a cheap nutritious food besides being a foreign exchange earner.

10 Integrated Multi Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable and innovative approach that cultivates multiple species from different trophic levels within the same aquatic system. By utilizing the waste products of one species as nutritional inputs for another, IMTA creates a closed-loop system that reduces environmental impact and maximizes resource efficiency. In a typical IMTA configuration, three distinct groups are cultured: primary high-value finfish (e.g., salmon or trout), secondary filter-feeders or detritivores (e.g., shellfish or sea cucumbers), and tertiary extractive species (e.g., seaweeds or algae). The primary species produces waste in the form of uneaten feed and fecal matter, which microorganisms convert into dissolved nutrients. These are then sequestered by the secondary and tertiary species, transforming potential pollutants into valuable biomass while significantly improving water quality.

IMTA offers significant advantages, including enhanced biodiversity and improved economic resilience through crop diversification. By recycling nutrients and reducing reliance on external inputs, this model aligns with "Blue Transformation" programs, integrating seaweed and bivalve farming with finfish cages (FAO, 2022b). Globally, aquaculture has grown at an average annual rate of 5.3% from 2001 to 2018, with IMTA gaining recognition for its role in enhancing food security (Barange et al., 2014). Despite its promise, the approach requires optimized system design to manage disease risks and ensure species compatibility. As seafood demand rises, IMTA provides a framework for climate-resilient practices by utilizing climate-tolerant native species and promoting water conservation (Goh et al., 2023).

Effective waste management in IMTA mitigates the negative impacts of intensification-such as soil and water degradation, fish stress, and reduced profitability (Asgard et al., 1998). By operating across different trophic levels, these systems function as complementary ecosystems where by-products are converted into fertilizer and energy for other crops (Jana et al., 2000). Utilizing acclimatized native species further ensures efficient bio-mitigation and sustained biomass growth. Ultimately, diversifying the production system keeps water quality parameters within balanced levels, achieving long-term sustainability in global food security (Kibria and Haque, 2018).

11 Biofloc Technology

Biofloc Technology (BFT) in aquaculture and the animal food industry represents a shift toward increasing biomass by maintaining a higher carbon-to-nitrogen (C:N) ratio. This ratio is essential to stimulate the establishment of a microbial community, primarily consisting of heterotrophic bacteria, which aggregate into significant clusters or "flocs" (Emerenciano et al., 2013). This technology has gained global popularity in countries such as South Korea, Brazil, China, Italy, Indonesia, Australia, and India. The microbial community plays a crucial role in managing water quality and providing a sustained supply of supplemental nutrition for the cultivated species. Recent investigations in rapidly urbanizing areas have further interpreted the relationship between efficient resource utilization in BFT and the reduction of carbon emissions (Yao et al., 2023). BFT systems are most effective with species such as tilapia and prawns that can directly consume the floc, leading to significantly increased production output while minimizing negative environmental impacts.

In the late 1980s and 1990s, research in Israel and the USA specifically at the Waddell Mariculture Centre-initiated studies on biofloc technology across multiple species, including *Penaeus monodon*, *Fenneropenaeus merguiensis*, *Litopenaeus vannamei*, and *L. stylirostris*. Their primary focus remained on tilapia and *L. vannamei* prawns. Commercial implementation of BFT first occurred at a farm in Tahiti (French Polynesia) in 1988, demonstrating beneficial features ranging from water quality control to in situ feed production. Currently, carp, catfish, tilapia, and shrimp are the species most commonly cultivated in biofloc systems (Alam and Khan, 2024; Raza et al., 2024). Further refinements in these systems were implemented following subsequent studies (Crab et al., 2012). For instance, the performance of freshwater prawns (*M. rosenbergii*) in low-density biofloc systems showed optimal growth and survival rates when managing stocking densities to maximize productivity.

Research in Bangladesh regarding the giant freshwater prawn, *M. rosenbergii*, demonstrated that biofloc helps reduce dietary protein requirements from 42% to 35% without compromising yield, allowing farmers to adopt more sustainable and cost-effective farming practices (Alam and Khan, 2024). Additionally, a 165-day study at Mindanao State University in the Philippines evaluated the effects of BFT on the water quality and growth performance of *M. rosenbergii*. The postlarvae of *M. rosenbergii* thrived as water parameters remained within the optimum range; interestingly, the technology did not significantly influence the dissolved oxygen, temperature, or pH values of the water and sediment samples (Camarin et al., 2023). These findings highlight the robustness of biofloc technology in maintaining stable aquatic environments for freshwater prawns while improving overall biological efficiency and resource management.

12 Recirculatory Aquaculture System

In recirculatory aquaculture system (RAS) water is recycled and reused after removal of suspended matter and metabolites and is used for high- density culture of various species of fish, utilizing minimum land area and water. It is suitable intensive high density fish culture unlike other aquaculture production systems instead of the traditional method of growing fish outdoors in open ponds and raceways in a controlled environment. Recirculating systems filter and clean the water by recycling it back to fish culture tanks. The technology is based on the use of mechanical and biological filters is used for species grown in aquaculture (Jham et al., 2024). The reconditioned water circulates through the system and less than 10% of the total water volume of the system is replaced daily in recirculation system. The management of recirculating systems relies heavily on the quantity and quality of feed and f filtration system used to remove metabolic wastes, excess nutrients, and solids from the water and provide good water quality. It encourages farmers and entrepreneurs and to facilitate fish production in urban and semi-urban areas where land and water resources are limited. In backyard Recirculation Aquaculture Systems is promoted RAS minimizes the risk of disease and promotes a healthier and more resilient aquaculture system keeping environmental conditions stable with increased production yields. The challenges reflects a significant challenge in agriculture, where high initial investment acts as a major barrier to economic viability and accessibility for small-scale farmers (Sedyaaw et al., 2025). RAS systems have been successfully implemented to produce various fish species, including Atlantic salmon, Arctic charr, rainbow trout, yellowtail king fish, the European seabass, and gilthead seabream (Supra Subhadarsani, 2024). H_2S-poisoning as a health hazard. RAS system can lead to both fish and other culture species. The RAS can assess adverse weather, unfavorable temperature conditions, external pollution and predation that can help achieve aquaculture production from limited waterbody (Shruti Gupta et al., 2024).

13 Introduction of Livestock and Organic Aquaculture

Here is the corrected portion of your manuscript. I have addressed the reviewer's comments by refining the academic language, improving the technical flow, and ensuring the distinction between integrated and organic systems is clear, while maintaining your original references, species names, and paragraph length. Livestock-fish farming is an integrated system that combines fish cultivation with livestock and poultry, allowing wastes from one component to serve as inputs for another. This synergistic approach is widely practiced across Indian states, including Tamil Nadu, Assam, Bihar, Andhra Pradesh, Tripura, Orissa, Karnataka, Kerala, and Uttar Pradesh. Currently, India supports approximately 17% of the global livestock population on only 2% of the world's geographical area, creating immense pressure on land resources and necessitating the integration of crops and livestock. This integration is mutually beneficial; animal manure serves as a potent natural fertilizer that enhances aquatic productivity while maintaining soil fertility. The diversity of species produced in these systems includes finfish, shellfish, mollusks, and aquatic plants.

While some species and production systems are difficult to adapt to strictly traditional "organic" frameworks, integrated farming shares a close relationship with organic aquaculture principles. This synergy is highly popular in Europe, where certified organic salmon, carp, and trout are cultivated and marketed. Similarly, mussels, tiger shrimp, white shrimp, and tilapia are cultured in diverse regions such as Vietnam, Peru, Ecuador, Chile, New Zealand, and Israel. These certified organic products have gained universal acceptance by addressing consumer health concerns (Dube and Chanu, 2012). Integrated crop-livestock-fish farming systems promote agricultural growth and environmental equilibrium by optimizing resource utilization and improving ecosystem services (Regar et al., 2022).

Poultry-fish farming is increasingly accepted and popular among farmers within integrated models. This practice involves raising birds such as chicken, ducks, and geese simultaneously with fish. The system significantly benefits aquaculture by utilizing poultry waste as a direct or indirect nutrient source, which reduces the dependency and cost associated with conventional fish meals. Consequently, this resource efficiency enhances the profit margins for small-scale and commercial producers (Gabriel et al., 2007). By recycling on-farm nutrients, these integrated models represent a sustainable pathway toward increasing food production while maintaining the ecological integrity of the farming environment.

14 Strategy for Higher Growth Rate

The development of coldwater fishery resources holds immense potential for generating rural income and providing food security to economically underprivileged populations in Indian upland regions. This is achieved through targeted aquaculture practices, ornamental fisheries, and sport fishery-based ecotourism. India has projected a sustained annual growth rate in its inland sector, characterized by an impressive Compound Annual Growth Rate (CAGR) of 8.58% from 2013-14 to 2023-24. While this growth aligns with national projections, the freshwater aquaculture sector faces specific constraints that require urgent attention for both horizontal and vertical expansion. The Himalayan region is blessed with an abundance of rivers, streams, and lakes across Jammu and Kashmir, Himachal Pradesh, Uttarakhand, West Bengal, Sikkim, Arunachal Pradesh, Nagaland, and Meghalaya. Similarly, the Western Ghats in Kerala, Tamil Nadu, Karnataka, and Maharashtra offer enormous resources for coldwater farming.

The lower temperature regimes in these regions support the farming of selected fast-growing species, including rainbow trout (*Oncorhynchus mykiss*), and exotic carps such as grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and common carp (*Cyprinus carpio*), alongside various exotic ornamental and minor carps. However, climate change, biodiversity loss, and over-exploitation remain significant challenges. ICAR-DCFR is actively promoting sustainable and responsible practices to improve infrastructure and reduce production waste (Sarma and Chandra, 2020). In the North Eastern region, particularly in Assam, Manipur, and Tripura, the exploitation of high-value indigenous fishes has gained priority due to high local consumption. Over 95% of the population in these states is involved in fish consumption, and meeting this demand requires intensive farming supported by appropriate technological interventions and infrastructure (Barman, 2012). While rural and tribal communities currently utilize small to medium-sized ponds, there remains tremendous scope for introducing fast-growing species tailored to the North East (Das, 2018).

Ornamental fish, abundantly distributed across freshwater, brackish, and inshore marine ecosystems, are gaining significant attention due to rising global and local demand. India possesses a high potential for the culture and export of ornamental varieties, many of which are easily accessible from wild resources for aquarium rearing. This sector fosters entrepreneurship, offering opportunities for individuals and women’s groups through small-scale backyard units or larger enterprises. By advancing breeding and farming techniques, there is a clear opportunity to boost production and increase foreign exchange (Raja et al., 2014). Government departments are now emphasizing modern fishing practices, the expansion of aquaculture, and effective technology transfer. Well-managed aquatic food systems, integrated with efficient value chains, are essential for ensuring food security and improving livelihoods (Sarkar et al., 2020; Prado-Carpio et al., 2021). Furthermore, adherence to certifications regarding food safety and animal welfare ensures that consumers receive healthier, safer products, thereby boosting the overall credibility of the industry (Amundsen and Osmundsen, 2020).

15 R & D Support Towards Blue Economy

To achieve a sustainable economy, India leverages various sectors-including fisheries, tourism, shipping, offshore energy, and biotechnology-as primary drivers for growth, livelihood improvement, and job creation for coastal and inland communities. India's ocean economy is expanding at an annual rate of 15%, with projections to exceed USD 120 billion by 2025. The nation is committed to socioeconomic prosperity by transforming the fisheries sector, promoting food security, and ensuring the judicious utilization of resources on a sustainable basis. Furthermore, India’s Integrated Coastal Zone Management (ICZM) program facilitates the sustainable management of coastal resources by balancing economic objectives with social and environmental considerations.

Central to these efforts is the Pradhan Mantri Matsya Sampada Yojana (PMMSY), which promotes fisheries development through infrastructure enhancement, robust marketing, and social security for fishers. Complementing this, the Integrated National Fisheries Action Plan (NFAP) is instrumental in achieving the goals of the Blue Revolution by addressing critical sustainability issues in aquaculture and ensuring long-term livelihood security. These strategic frameworks align modern production techniques with conservation goals, fostering a resilient aquatic economy that supports millions. By integrating technological innovation with policy reform, India continues to strengthen its position as a global leader in sustainable aquaculture and marine resource management.

16 Summary

Aquaculture faces significant environmental challenges, particularly regarding nutrient pollution and disease outbreaks. Consequently, understanding the causal relationships between production intensity, species diversification, and environmental impact is essential for developing effective strategies that support long-term sustainability and resilience. Current expansions in aquaculture and allied activities are strategically planned to address complex socio-economic and environmental constraints. India, in particular, emphasizes the balanced utilization of oceanic, coastal, and freshwater resources while prioritizing the preservation of ecosystem biodiversity. Sustainable technologies are being adapted to diverse agro-climatic conditions, integrating advanced diagnostics, aquatic pollution monitoring, and specialized therapeutics alongside the adoption of best management practices (BMPs).

The focus has shifted toward achieving sustainability by prioritizing the cultivation of native species within both open-water and improved closed-culture systems. A precautionary approach is applied to the use of genetically modified organisms, feed additives, and organochemicals, ensuring they undergo rigorous validation before implementation. To mitigate the risk of disease transmission, stocking densities are optimized to prevent physiological stress. Furthermore, coastal zones are protected through strict regulations on effluent discharge, ensuring that intensive operations do not compromise the surrounding environment or human health. The integration of innovative, eco-friendly technologies-such as Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and Biofloc Technology (BFT)-represents a transformative approach to organic and integrated farming, significantly enhancing both productivity and ecological integrity.

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