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Sustainability in Indian Aquaculture: Current Practices, Emerging Technologies, and the Road Ahead

[1]Dr. Vellala Subrahmanya Ramamurty, [2]Ms. Vinukonda Gayathri, [3]Ms. Rachakonda Vaishnavi, [4]Dr. B. D. Hansraj

[1]Professor, School of Management and Technology,

Malla Reddy Deemed to be University, Maisammaguda, Secunderabad

[2]Assistant Professor, School of Management and Technology,

Malla Reddy Deemed to be University, Maisammaguda, Secunderabad

[3]Assistant Professor, School of Management and Technology,

Malla Reddy Deemed to be University, Maisammaguda, Secunderabad

[4]Associate Professor, Department of MBA,

CMR College of Engineering and Technology, Kandlakoya, Medchal,Hyderabad

Abstract

Aquaculture has ascended to worldwide prominence, evolving into one of the leading industries on Earth today, and India has firmly established itself as a global leader in the aquaculture industry. India ranked as the world's second-largest aquaculture producer with a total output of 17.55 million metric tons recorded in 2022–23 (**Giri, 2024**). Unfortunately, the speed and scale of this expansion have come with a heavy environmental price through mangrove habitats degradation, deterioration and depletion of groundwater resources, suffocation of coastal ecosystems with high levels of nutrients, and an increased and indiscriminate use of antibiotics on farm (**Jayasankar, 2003; Khanjani et al., 2022**). This article presents a closer view of the present situation of Indian aquaculture which is leaning towards sustainable practices by examining the various practices being deployed across freshwater aquaculture, brackish-water shrimp culture, and the fast-growing mariculture frontier. By applying latest technologies like Integrated Multi-Trophic Aquaculture (IMTA), Biofloc Technology (BFT), Re-circulating Aquaculture Systems (RAS), many of these problems can be solved. The article also studies some of the important programs initiated by government such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and the Coastal Aquaculture Authority (CAA) that are helping to reshape the aquaculture practices towards sustainability. This paper also highlights the various issues in antibiotic governance, certification aspects, and climate preparedness towards sustainability. Through this study, directions toward ecologically responsible , economically resilient, and genuinely inclusive aquaculture practices are identified.

Keywords: Sustainable aquaculture, biofloc technology, antimicrobial resistance, shrimp farming, food security, PMMSY

1. Introduction

Aquaculture is a distinct one among all the food production systems that have grown in the past three decades. While most agricultural sectors have expanded incrementally, aquaculture has undergone what can only be described as a revolution—global output climbing by more than 600% since 1990, and the sector growing at an average annual rate of 5.3% between 2001 and 2018 (**Ahmed & Turchini, 2021**). This surge has been propelled by a stubborn reality: wild-capture fisheries have essentially plateaued, with global marine landings averaging around 78.8 million tons per year through the 2010s—notably below the 81.9 million tons recorded in the 1990s (**FAO, 2022**). As capture fisheries stagnate and world population continues to climb, aquaculture has become the indispensable bridge between seafood demand and supply.

Within this global picture, India occupies a position of exceptional importance. The country's aquaculture and fisheries sector produced 17.55 million metric tons in 2022–23, split between 4.43 million tons from marine sources and 13.11 million tons from inland waters (**Giri, 2024**). Beyond the raw figures, the sector underpins the livelihoods of more than 14 million people in coastal and inland communities and contributes over ₹1.2 lakh crore annually to the national economy (**Ramamurty & Rao, 2025**). In the mid-1980s, aquaculture contributed roughly 34% of total inland fish production; today that share has risen to approximately 65%, reflecting one of the most striking structural shifts in Asian food systems (**FAO, 2024**).

This growth has also been economically dynamic. Between FY2011 and FY2023, India's fisheries and aquaculture sector expanded its gross value of output at 8.2% per year—nearly three times the pace of cereal agriculture and almost double the growth rate of the broader agriculture and allied sectors (**ICRIER, 2024**). The engine of this expansion has largely been brackish-water shrimp cultivation, specifically of the Pacific whiteleg shrimp *Litopenaeus vannamei*, which reached 9.30 lakh tonnes in 2021 before encountering headwinds from disease, volatile input costs, and shifting market conditions (**Giri, 2024**).

But growth at this pace carries environmental consequences that can no longer be treated as peripheral concerns. Intensive aquaculture has been linked to landscape transformation, soil and groundwater salinization, loss of mangrove habitat, depletion of coastal biodiversity, eutrophication of receiving water bodies, and the proliferation of antibiotic-resistant bacteria (**Jayasankar, 2003; Khanjani et al., 2022**). In 2018, the global aquaculture industry was responsible for an estimated 261.3 million tons of greenhouse gas emissions and consumed 122.6 km^3 of freshwater; India ranked second globally in both categories, behind only China (**Liu et al., 2022**). These figures underscore the depth of structural change that must accompany any credible sustainability transition.

Digital technologies offer transformative solutions that balance productivity with ecological responsibility. **Ramamurty and Rao (2025)** argue that digital transformation in aquaculture is not merely a technological shift but a paradigm change toward resilient and inclusive aquatic food systems, with their interdisciplinary framework integrating IoT, AI, blockchain, and GIS demonstrating how data-driven approaches can simultaneously improve farm efficiency, enhance supply chain transparency, and reduce ecological harm. The Government of India has responded through the Pradhan Mantri Matsya Sampada Yojana (PMMSY), launched in September 2020 with an outlay of ₹20,050 crore (**PIB, 2024**). This review synthesizes the current state of sustainable aquaculture practices in India and charts a realistic path forward for a sector whose future is as consequential for rural India as any in the country's food system.

2. India's Aquaculture Landscape: Species, Geography, and People

2.1 What India Farms and Where

India's aquaculture base is remarkably diverse. In freshwater systems, production is anchored by Indian Major Carps (IMC) Catla catla, Labeo rohita, and Cirrhinus mrigala cultivated in traditional carp polyculture ponds across nearly every state. West Bengal, Andhra Pradesh, Uttar Pradesh, Bihar, and Odisha are the major freshwater production hubs, and carp farming remains the principal livelihood activity for millions of inland farm households (**Jayasankar, 2003**).

Brackish-water shrimp cultivation is concentrated along the eastern coastline, with Andhra Pradesh and Odisha together accounting for over 70% of national shrimp production. L. vannamei has progressively displaced the native black tiger shrimp Penaeus monodon, now representing over 80% of farmed shrimp output owing to faster growth rates, higher stocking tolerances, and better disease resilience (**Giri, 2024**). In 2021, India's farmed shrimp production stood at 9.20 lakh tonnes, cementing the country's position as the world's largest shrimp exporter by volume (**PIB, 2024**).

Mariculture, a farming in open coastal and offshore marine environments is an emerging frontier. Open sea cage culture, which began experimentally in the Bay of Bengal off Visakhapatnam in 2007, has expanded to include commercially valuable species such as cobia (Rachycentron canadum), silver pompano (Trachinotus blochii), and milkfish (Chanos chanos) (**Nair et al., 2025**). Seaweed cultivation, particularly of Kappaphycus alvarezii and

Gracilaria spp. along Tamil Nadu, Gujarat, and Maharashtra coasts, is gaining ground both as a commercial enterprise and as a biological tool for coastal nutrient management (**Sasikumar & Viji, 2015**).

Table 1: India's Aquaculture Sector – Key Production and Economic Indicators

Indicator	2018–19	2022–23	PMMSY Target 2024–25
Total Fish Production (MMT)	13.70	17.55	22.0
Inland Production (MMT)	9.70	13.11	~15.0 (est.)
Marine Production (MMT)	3.70	4.43	~5.5 (est.)
Shrimp Export Volume (lakh MT)	5.85	7.40 (est.)	—
Annual Sector Revenue (₹ lakh crore)	~0.85	~1.20	—
Direct Livelihoods (million people)	~12	~14	~19 (incl. indirect)

Sources: Giri (2024); PIB (2024); FAO (2024); ICRIER (2024); Ramamurty & Rao (2025).

2.2 The Human Dimension

It is easy to reduce aquaculture to production volumes and export figures, but the sector's most consequential dimension may be its human one. Over 14 million people draw direct livelihoods from fish farming and fishing in India, while millions more depend on allied industries such as feed manufacturing, processing, cold chain logistics, and retail (**Ramamurty & Rao, 2025**). **Edwards et al. (2023)** have documented how market-led expansion of freshwater fish culture has underpinned significant income gains for rural households in key aquaculture states, particularly where public-sector investment in seed supply and extension services has been effective.

Women are increasingly visible across India's aquaculture value chain—particularly in post-harvest processing, fish vending, and market-oriented cooperatives. MPEDA's National Centre of Sustainable Aquaculture (NaCSA) has made targeted efforts to organize shrimp farmers, including women, into aquaculture societies and deliver capacity-building at the farm level (**MPEDA, 2024**). Despite this progress, gender-disaggregated data on women's roles in primary production remains thin, and barriers to women's access to land titles, credit facilities, and technical training persist in ways that limit the sector's full human capital potential.

3. Environmental Costs of Conventional Aquaculture

3.1 Mangrove Loss and Coastal Habitat Damage

The rapid spread of brackish-water shrimp ponds along India's eastern coast has historically come at the direct expense of mangrove forests, ecosystems that simultaneously serve as nursery habitats for fish and crustaceans, carbon sinks of global significance, natural coastal protection, and filters that intercept land-based nutrient pollution before it reaches open water (**Jayasankar, 2003**). While India's Coastal Regulation Zone (CRZ) notifications and the Coastal Aquaculture Authority Act of 2005 provide a legal framework to restrict aquaculture in ecologically sensitive zones, enforcement has been uneven and, in states like Andhra Pradesh and Odisha, often inadequate to halt encroachment on mangrove land (**MPEDA, 2024**).

3.2 Water Pollution and Eutrophication

Shrimp ponds operated at intensive stocking densities discharge effluents carrying elevated loads of nitrogen, phosphorus, and organic matter. When released untreated into adjacent creeks, lagoons, and estuaries, these discharges fuel algal blooms, deplete dissolved oxygen, and degrade water quality across far wider catchment areas than the farms themselves. Research tracking Indian aquaculture from 2016 to 2020 documented a 6.08% increase in farming extent, accompanied by measurable increases in ammonia and nitrate concentrations in receiving water bodies (ResearchGate, 2022). The release of nitrogen at 1.6 Mt/year and phosphorus at 0.2 Mt/year from intensive aquaculture has been recorded in comparable Asian coastal systems (**Liu et al., 2022**), indicating the scale of potential nutrient loading. Beyond surface water, aquaculture leachate can percolate into adjacent soils, altering mineralogy and hydraulic conductivity in ways that affect neighboring agricultural land.

3.3 The Antimicrobial Resistance Crisis

If there is a single sustainability challenge in Indian aquaculture that carries both domestic and global consequences, it is antimicrobial resistance. Antibiotics, including oxytetracycline, sulphamethoxazole, ciprofloxacin, trimethoprim, and chloramphenicol have been applied in shrimp and fish culture with limited regulatory oversight, and residues have been detected in pond water, pond sediments, and the marketed products themselves (**Rakesh et al., 2018, cited in ScienceDirect, 2024**). India ranks second globally in the volume of AMR-related aquaculture research publications, a reflection of the scale of the problem (**Caputo et al., 2023**).

Surveillance through the Indian Network for Fisheries and Animal Antimicrobial Resistance (INFAAR) across multiple states like Andhra Pradesh, Tamil Nadu, Maharashtra, Kerala, and Gujarat has identified Vibrio spp. and Aeromonas spp. as the most prevalent resistant organisms, with beta-lactamases, tetracyclines, sulfonamides, macrolides, and fluoroquinolones as the dominant resistance classes detected (**Caputo et al., 2023**). The horizontal transfer of antimicrobial resistance genes (ARGs) between pathogenic and commensal bacteria represents a pathway through which aquaculture environments become reservoirs of clinically relevant resistance (**Murugadas et al., 2019, cited in ScienceDirect, 2024**). Antibiotic residues detected in exported shrimp have triggered consignment rejections by trading partners in Europe and North America, directly threatening export revenue (**MPEDA, 2024**).

Table 2: Antimicrobial Resistance in Indian Aquaculture – Key Antibiotic Classes and Regulatory Status

Antibiotic Class	Species Context	Key Resistant Organisms	Regulatory Status in India
Tetracyclines	Vannamei, P. monodon shrimp	Vibrio spp., Aeromonas spp.	Banned without prescription; NRCP monitored
Sulfonamides	Finfish, shrimp hatcheries	Aeromonas hydrophila	Restricted; INFAAR surveillance
Fluoroquinolones	Shrimp culture ponds	Multi-drug resistant Vibrio	Banned in export produce; EU/US zero-tolerance
Chloramphenicol	Shrimp, freshwater fish	Gram-negative pathogens	Fully banned; consignment rejection trigger
Beta-lactams	Hatchery disease treatment	Resistant Pseudomonas spp.	Prescription-only; limited rural surveillance

Sources: Caputo et al. (2023); Murugadas et al. (2019); MPEDA (2024); ScienceDirect (2024); Schar et al. (2020).

3.4 Climate Change and Compounding Risks

Indian aquaculture is on the front line of climate change impacts. Rising sea surface temperatures, shifting monsoon dynamics, increased frequency and intensity of cyclonic storms, salinity fluctuations in coastal estuaries, and sea level rise all interact with aquaculture systems in ways that can be devastating in combination. **Adhikari et al. (2018)** have documented adaptation and mitigation challenges facing freshwater aquaculture across multiple Indian states, noting that temperature extremes alter feeding behaviour, immune function, reproductive cycles, and disease susceptibility in farmed species. Coastal farms in low-lying delta areas face growing risks of tidal inundation and storm surge damage, with serious production losses already recorded in Andhra Pradesh and Odisha during recent cyclone seasons (**Yadav et al., 2024**).

4. Sustainable Technologies:

4.1 Integrated Multi-Trophic Aquaculture (IMTA)

The core logic of IMTA is ecological efficiency: instead of viewing the waste products of farmed species as a problem to be managed, IMTA treats them as inputs for other species, creating a closed-loop system that dramatically reduces nutrient discharge and improves overall resource productivity (**Khanjani et al., 2022**). A typical IMTA configuration pairs a fed species like shrimp or finfish consuming formulated feed with organic extractive species such as shellfish or sea cucumbers that feed on particulate waste, and inorganic extractive species such as seaweeds that absorb dissolved nutrients (**Sasikumar & Viji, 2015**). Each tier performs a distinct ecological function, and together they create a system substantially more efficient and less polluting than any single-species monoculture.

In India, ICAR-CIBA has developed IMTA frameworks adapted to coastal and estuarine conditions, including collaborative work with Maharashtra's Mangrove Cell promoting IMTA in Sindhudurg district. Kappaphycus alvarezii has emerged as a particularly effective inorganic extractive partner for shrimp culture systems along the southern and western coasts (CMFRI, cited in EPRINTS CMFRI, 2015). Research demonstrates that shrimp IMTA systems show superior feed conversion ratios, weight gain, and growth compared to monoculture, while simultaneously reducing effluent nitrogen and phosphorus loading (**Khanjani et al., 2022**). When combined with Biofloc Technology, IMTA systems have demonstrated the capacity to more than double shrimp biomass production compared to monoculture controls, with tilapia consuming and managing total suspended solids without compromising water quality (**Holanda et al., 2022, cited in ScienceDirect, 2025**). Economic analyses from Indian pen systems confirm that IMTA generates higher net income and better benefit-cost ratios than monoculture, while also providing natural insurance against single-species price volatility and disease risk (**Balasubramanian et al., 2018**).

4.2 Biofloc Technology (BFT)

Biofloc Technology works by deliberately engineering the microbial community within a culture pond. By maintaining a high carbon-to-nitrogen (C:N) ratio through additions of cheap carbon sources such as molasses or wheat bran, farmers stimulate the proliferation of heterotrophic bacteria that rapidly assimilate ammonia into their own biomass (**Nair et al., 2025**). The resulting microbial flocs comprising bacteria, protozoa, microalgae, and organic detritus serve a dual function: they biologically assimilate nitrogenous wastes, thereby maintaining water quality, and they provide a supplementary protein-rich feed source for cultured organisms, reducing external feed requirements (**Khanjani et al., 2022**). Crucially, BFT systems operate with minimal water exchange, simultaneously conserving freshwater and preventing the discharge of nutrient-laden effluents into surrounding waterways.

BFT has become one of PMMSY's flagship sustainable technologies, with over 52,000 biofloc units deployed across India as of recent program reports (**PIB, 2024**). E-learning modules on biofloc operation were developed and disseminated during the COVID-19 pandemic to reach farmers in remote areas (IJRIAS, 2025). Farm-level research in Andhra Pradesh and Tamil Nadu has shown that well-managed BFT systems suppress pathogen proliferation through competitive exclusion, reducing antibiotic use while raising production per unit pond area (**Khanjani et al., 2022**). The main operational challenge accumulation of total suspended solids over time can be addressed through integration with IMTA components such as filter-feeding shellfish or nutrient-absorbing seaweeds.

4.3 Recirculating Aquaculture Systems (RAS)

RAS represents the apex of technological intervention in sustainable aquaculture, a production system in which culture water passes through a sequential chain of treatment processes, is restored to near-optimal quality, and is returned to the culture tank, with typically 95–99% of water reused in each cycle (**Ahmed & Turchini, 2021**). Drum filters remove suspended solids; nitrifying biofilters convert toxic ammonia to relatively harmless nitrate; degassing units strip excess carbon dioxide; and supplemental oxygenation maintains dissolved oxygen at optimal levels. This engineering-intensive design allows RAS facilities to operate at stocking densities up to 100 times higher than conventional pond systems (**Sarosh et al., 2024**), while generating a fraction of the effluent volume.

For Indian aquaculture, RAS's greatest asset beyond productivity may be its climate resilience. Operating in controlled indoor or semi-enclosed environments, RAS facilities are effectively insulated from the temperature extremes, salinity shifts, monsoon variability, and cyclonic disruptions that increasingly compromise outdoor pond farming (**Ahmed & Turchini, 2021**). RAS has been adopted in the Indian Himalayan Region for cold-water species such as trout, where **Sarkar et al. (2022)** document it as substantially reducing dependence on water and land resources while providing a framework for high-value species production. The primary barriers to wider adoption remain capital cost and energy consumption factors that make parallel investment in renewable energy integration essential if RAS is to scale sustainably (**Yadav et al., 2024**).

4.4 Rice-Cum-Fish Culture and Integrated Farming

Not all sustainable aquaculture involves high technology. Rice-cum-fish culture, the concurrent or alternating cultivation of rice and fish or shrimp within the same paddy field is one of India's oldest integrated farming traditions. Fish waste fertilizes the rice field, reducing dependence on synthetic nitrogen; fish and shrimp consume aquatic weeds and insect pests, reducing pesticide requirements; and the net effect is a farming system that produces both staple grain and animal protein from the same land area with lower external inputs than either crop alone (**Jayasankar, 2003**). The system is widespread in West Bengal, Odisha, Manipur, and Assam, where it functions as both a food security strategy and a cultural farming identity.

Integrated fish-livestock systems where fish are co-cultured with poultry or pigs, with animal waste used as pond fertilizer are also practiced at smallholder scale and represent efficient nutrient cycling models within the farm boundary. While careful management is required to prevent pathogen transfer, these systems can substantially reduce external input costs. **Jayasankar (2003)** identifies integrated farming models as fundamental to long-term rural aquaculture sustainability in India, provided appropriate veterinary and extension oversight is available to small and marginal farmers.

4.5 Probiotics and Reducing Antibiotic Dependence

The search for effective alternatives to prophylactic antibiotic use has become one of the most active areas of applied aquaculture research globally, and India is no exception. Probiotics preparations of beneficial microbial strains, primarily Bacillus and Lactobacillus species have demonstrated capacity to reduce disease incidence in shrimp and finfish, improve feed conversion ratios, and maintain water quality through competitive exclusion of pathogenic bacteria (**Jayasankar, 2003; Khanjani et al., 2022**). Field experience in Indian shrimp farms confirms that probiotic use as part of a biosecurity protocol can reduce the frequency of antibiotic interventions while maintaining or improving production outcomes.

Beyond probiotics, researchers are investigating phage therapy, plant-derived antimicrobial compounds, immunostimulants, essential oils, Prebiotics, and synbiotics as complementary disease management tools (**Frontiers in Aquaculture, 2026**). At the institutional level, MPEDA's SHAPHARI certification program which tests farms, hatcheries, and feed mills across consecutive production cycles for banned antibiotic residues provides a market-facing incentive for chemical-free production. The National Residue Control Program (NRCP) extends systematic surveillance across both export and domestic market channels, and MPEDA's Pre-Harvest Testing

(PHT) certification allows certified farms to demonstrate compliance to international buyers before harvest (**MPEDA, 2024**).

4.6 Precision Aquaculture and Digital Technologies

The integration of real-time monitoring and data-driven decision-making into farm management broadly termed precision aquaculture is beginning to reshape commercial-scale operations in India. IoT-based sensor arrays that continuously track dissolved oxygen, pH, temperature, salinity, and turbidity can flag deteriorating water quality before it triggers mass mortality events (**Nair et al., 2025**). Machine learning models integrating GIS data with farm production records have been applied to disease risk forecasting in shrimp farms, potentially enabling preventive action rather than reactive treatment (**Khiem et al., 2022, cited in Frontiers in Aquaculture, 2026**).

Computer vision technologies including deep-learning YOLOv8-based models applied to pond footage—have been used in ICAR trials to estimate fish biomass with accuracy exceeding 94%, enabling precise automated feed delivery that minimizes wasteful overfeeding that contributes directly to eutrophication (**Hossam et al., 2024, cited in Frontiers in Aquaculture, 2026**). Deep neural network models applied to image datasets have demonstrated capacity for early disease detection in shrimp, reducing the lag time between pathogen appearance and clinical intervention. However, these technologies remain largely confined to large-scale commercial operations with capital and technical capacity; democratizing precision aquaculture to reach smallholder farmers through affordable sensor networks and mobile-based advisory platforms is a prerequisite for its contribution to India's broader sustainability transition (**Ramamurty & Rao, 2025**).

Table 3: Comparison of Key Sustainable Aquaculture Technologies in Indian Aquaculture

Technology	Water Use	Land Efficiency	Capital Cost	Best Suited For
IMTA	Moderate	High	Low–Medium	Coastal/estuarine farms; multi-species integration
Biofloc (BFT)	Very Low	High	Medium	Shrimp & tilapia ponds; minimal-exchange systems
RAS	Minimal (95–99% reuse)	Very High	Very High	High-value finfish; cold-water and climate-exposed zones
Rice-cum-Fish	Low (shared field)	Moderate	Very Low	Smallholder rainfed paddy farming communities
Precision Aquaculture	Moderate	High	Medium–High	Commercial-scale operations with digital infrastructure

Sources: Ahmed & Turchini (2021); Khanjani et al. (2022); Nair et al. (2025); Sarosh et al. (2024); Jayasankar (2003).

5. Policy and Regulatory Framework

5.1 Pradhan Mantri Matsya Sampada Yojana (PMMSY)

Launched on 10 September 2020 under the Ministry of Fisheries, Animal Husbandry and Dairying, PMMSY is the most ambitious fisheries and aquaculture policy intervention India has ever undertaken (**PIB, 2024**). With a total investment of ₹20,050 crore allocated over five years, the scheme targets raising total fish production to 22 million tons by 2024–25, doubling farmer incomes, creating 5.5 million new employment opportunities, halving post-harvest losses, and ensuring that this growth is ecologically sustainable. The scheme has moved beyond aspiration into measurable action: over 52,000 reservoir cages have been established, thousands of biofloc and RAS units set up across states, and more than 23,000 hectares of previously unproductive water bodies brought into productive aquaculture use, targeting productivity of 6.5 tonnes per hectare by 2029 (**PIB, 2024; AgroTech Space, 2025**).

A complementary sub-scheme—the Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY), launched in 2023 with a ₹6,000 crore outlay—focuses specifically on formalising micro and small fisheries enterprises and extending financial inclusion to the long-underserved informal sector of the fisheries economy (**PIB, 2024**).

5.2 Coastal Aquaculture Authority (CAA) and MPEDA

The Coastal Aquaculture Authority (CAA), established under the Coastal Aquaculture Authority Act of 2005, is the statutory licensing and regulatory body for all aquaculture activities in India's coastal zones. CAA licenses are issued only after verification that farm inputs—including feeds and chemical inputs—are free of banned substances, and compliance conditions include water quality management, effluent disposal standards, habitat and mangrove protection obligations, and biosecurity requirements (**MPEDA, 2024**). In practice, enforcement capacity has not always matched regulatory ambition, and a significant proportion of coastal farms continue to operate outside formal licensing frameworks.

MPEDA operates in a complementary space, promoting international certification standards including Best Aquaculture Practices (BAP) and HACCP across the export supply chain, coordinating extension services through NaCSA, and administering the SHAPHARI certification program (**MPEDA, 2024**). MPEDA's Pre-Harvest Testing system which allows farmers to certify produce as free of specified antibiotic residues before harvest has become a key tool for maintaining access to premium export markets in Europe, the United States, and Japan. India's National Residue Control Program (NRCP) provides additional surveillance through systematic testing of aquaculture produce and inputs in the national market.

5.3 International Frameworks and SDG Linkages

India's aquaculture sustainability agenda sits within a broader international architecture. The United Nations SDGs most directly relevant are SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). The FAO's 2022 State of World Fisheries and Aquaculture report—subtitled 'Towards Blue Transformation' provides the normative global framework against which India's policies are benchmarked (**FAO, 2022**). FAO has been an active partner through the Bay of Bengal Program and the Bay of Bengal Large Marine Ecosystem (BOBLME) project, both of which advance ecosystem-based fisheries management approaches relevant to Indian coastal aquaculture.

India's National Action Plan on AMR, aligned with the WHO Global Action Plan on Antimicrobial Resistance (2015), includes aquaculture provisions though their implementation across the fragmented, dispersed small-farm sector remains a work in progress (**Caputo et al., 2023**). Integration of aquaculture-specific AMR targets into national policy documents represents a priority for aligning India with the WHO One Health approach, which recognises the interconnectedness of human health, animal health, and environmental health in addressing resistance.

Table 4: India's Key Aquaculture Policy and Regulatory Interventions

Policy / Programme	Year	Key Objectives	Sustainability Focus
PMMSY	2020	Raise production to 22 MMT; double farmer incomes; create 5.5M jobs	BFT, RAS, cage culture, cold chain development

Policy / Programme	Year	Key Objectives	Sustainability Focus
PM-MKSSY	2023	Formalization of small fish enterprises; financial inclusion	Micro-enterprise support, credit access
CAA Act	2005	Regulate coastal aquaculture; prevent mangrove loss	Licensing, effluent norms, banned substance controls
MPEDA SHAPHARI	2016	Certification of farms, hatcheries, feed mills for antibiotic-free production	AMR control; export market compliance
National AMR Action Plan	2017	One Health approach to AMR across human, animal, aquatic sectors	Surveillance, prescription controls, awareness

Sources: PIB (2024); MPEDA (2024); CAA Act (2005); Caputo et al. (2023); FAO (2022).

6. Persistent Challenges and Critical Gaps

Despite the considerable progress achieved through policy reform and technological innovation, the transition to fully sustainable aquaculture in India faces structural, institutional, and knowledge-related constraints that must be addressed with urgency.

The fragmentation of India's aquaculture sector is perhaps the most fundamental constraint. The vast majority of fish and shrimp farmers operate holdings of between 0.5 and 2 hectares scales at which the capital requirements of technologies like RAS or fully automated precision aquaculture systems are simply prohibitive (**ICRIER, 2024**). While PMMSY and the Kisan Credit Card (KCC) scheme have expanded financial access, credit absorption remains uneven across regions and farmer categories, and the risks of technology adoption continue to fall disproportionately on smaller, more vulnerable farmers.

Certification and regulatory compliance are inconsistent in ways that create both equity and market integrity problems. Many shrimp farms in coastal regions operate without CAA licenses, and awareness of Good Aquaculture Practice standards remains low among resource-poor farmers distant from extension services. The coexistence of multiple certification schemes such as BAP, HACCP, GlobalG.A.P., SHAPHARI creates compliance complexity that can inadvertently favour large, vertically integrated enterprises at the expense of smallholders (**MPEDA, 2024**).

AMR governance at the farm level remains a critical weakness. Antibiotics are openly sold over the counter in many aquaculture supply markets without veterinary prescription, and surveillance through INFAAR and other programs does not reach into the dispersed network of small rural farms where most non-compliant antibiotic use actually occurs (**Caputo et al., 2023; Schar et al., 2020**). Enforcement of restrictions on banned substances is constrained by both limited testing capacity and inadequate penalty structures.

Environmental impact accounting for Indian aquaculture is underdeveloped. Life cycle assessments for Indian aquaculture systems are scarce, making it difficult to systematically quantify the net environmental impact of specific sustainability interventions or to benchmark India's performance against comparable aquaculture nations (**Liu et al., 2022**). Without robust LCA data, evidence-based policy prioritisation is constrained.

Finally, climate vulnerability research specific to Indian aquaculture remains inadequate relative to the urgency of the challenge. Farm-level adaptation strategies including species diversification, selective breeding for climate-resilient strains, and geographic relocation of production require substantially greater research investment and policy support than they have so far received (**Yadav et al., 2024**).

Table 5: Key Challenges in Indian Aquaculture Sustainability – Issues and Recommended Pathways

Challenge Area	Core Issue	Recommended Pathway
Smallholder Exclusion	Capital-intensive RAS and precision tech remain out of reach for 0.5–2 ha farms	Group certification; PMMSY subsidies linked to environmental performance benchmarks
AMR Governance	Over-the-counter antibiotic sales; weak surveillance penetration in rural areas	Prescription-only dispensing; expanded INFAAR monitoring network
Certification Gaps	Low awareness of GAP/HACCP; compliance complexity excludes smallholders	Simplified collective compliance; streamlined multi-scheme alignment
Environmental Accounting	Scarcity of Indian LCA data; difficult to benchmark net ecological impact	ICAR-led LCA research program; national ecological footprint database
Climate Adaptation	Farm-level vulnerability rarely assessed; species-specific adaptation lacking	District vulnerability mapping; selective breeding for climate-resilient strains

Sources: ICRIER (2024); Caputo et al. (2023); MPEDA (2024); Yadav et al. (2024); Ahmed & Turchini (2021); Liu et al. (2022).

7. Recommendations for Accelerating the Transition

The evidence reviewed in this article supports the following evidence-based recommendations for policy makers, research institutions, and industry stakeholders:

- Integrate sustainable technologies systematically: IMTA, BFT, and RAS should be promoted as complementary components of a systems-based production framework, not isolated interventions (Khanjani et al., 2022; Ahmed & Turchini, 2021). Pilot demonstration farms that integrate all three co-funded by state fisheries departments, ICAR institutions, and private partners would generate farm-applicable evidence and build farmer confidence. Technology subsidies under PMMSY should be linked to verified environmental performance benchmarks rather than technology installation alone (PIB, 2024).
- Strengthen AMR governance with enforcement capacity: A national aquaculture AMR surveillance network, coordinated through ICAR-CIBA and state veterinary authorities, should mandate regular monitoring in high-production districts (Caputo et al., 2023). Over-the-counter antibiotic sales to aquaculture farmers should be phased out through a transition to prescription-based dispensing, supported by expanded training of aquaculture veterinarians and extension officers. Certification and market-access incentives for farms demonstrating verifiable antibiotic-free production should be strengthened (MPEDA, 2024).
- Design sustainability programs to reach the smallest farmers: Simplified compliance pathways, group certification models for farmer producer organisations, and peer-to-peer technology learning within cooperatives would extend the reach of sustainability programs beyond the large commercial operations that currently absorb the bulk of scheme benefits (ICRIER, 2024; Edwards et al., 2023). Women's participation in sustainable

aquaculture value chains should be explicitly targeted through gender-responsive extension, dedicated credit products, and secure land tenure support (MPEDA, 2024).

• Build digital infrastructure for inclusive precision aquaculture: Investment in affordable IoT sensor networks, mobile-based advisory platforms, and satellite-based pond monitoring would extend precision aquaculture beyond large commercial farms into smallholder systems (Ramamurty & Rao, 2025). Public-private partnerships leveraging India's established IT sector could accelerate the development and deployment of locally adapted, low-cost digital solutions calibrated to the actual operating conditions and data literacy of small-scale farmers (Nair et al., 2025).

• Operationalise climate adaptation planning for aquaculture: District-level climate vulnerability mapping for aquaculture should be developed as a spatial planning tool to guide decisions about farm siting, species selection, and infrastructure investment (Yadav et al., 2024). Selective breeding programs for climate-resilient strains of Indian Major Carps and L. vannamei should be prioritised at ICAR national centers, and policy support for species diversification as a climate risk management strategy should be built into scheme eligibility criteria.

8. Conclusion

India's aquaculture sector stands at a pivotal inflection point. The extraordinary production growth of recent decades—reaching 17.55 million metric tons in 2022–23 (**Giri, 2024**) has created real opportunities for food security, rural employment, foreign exchange earnings, and poverty reduction. But that growth has also generated ecological pressures and governance deficits that, left unaddressed, could undermine the long-term viability of the sector itself.

The evidence reviewed here demonstrates that a range of sustainable practices IMTA, BFT, RAS, rice-cum-fish culture, and probiotic-based disease management offer technically proven pathways to reconciling productivity with environmental responsibility (**Khanjani et al., 2022; Ahmed & Turchini, 2021; Jayasankar, 2003**). The Indian government has committed substantial resources through PMMSY and allied schemes (**PIB, 2024**), and the regulatory architecture of CAA, MPEDA, and NaCSA provides an institutional foundation on which more rigorous and equitable sustainability governance can be constructed (**MPEDA, 2024**).

Realising the full potential of these frameworks requires sustained attention to smallholder inclusion, AMR governance, climate adaptation planning (**Yadav et al., 2024**), and ecological impact monitoring (**Liu et al., 2022**). Aquaculture's contribution to India's Blue Economy will depend not merely on production volumes, but on the ecological integrity and social equity with which those volumes are generated. A science-informed, innovation-driven, and farmer-centered approach to sustainable aquaculture offers a credible pathway toward that goal—and achieving it is among the most consequential challenges facing Indian food systems policy in the coming decade.

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