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Review Article

Sustainable Aquaculture by Bio-Ecological Remediation of Freshwater Aquaculture Environments

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Abstract

Success in the aquaculture sector in India is evidenced by its extensive contributions to food security, since the fish captured from fresh water and marine bodies are unable to meet the existing requirement for fish in the country. Interest in sustainable aquaculture and the "blue economy" has intensified globally, with freshwater aquaculture increasingly being recognized as a scalable route to reducing hunger, generating rural livelihoods, and diversifying nutrition-sensitive food systems. The current evidence on the ecological and economic outcomes of bio-ecological remediation in freshwater aquaculture systems is being reviewed synthesizing the state of knowledge and identifying gaps that constrain wider adoption. Building on our earlier field initiative designed to secure sustainable livelihoods and food security in an Indian state where close to 100 million people live below the poverty line, with an emphasis on land-based and freshwater aquaculture aligned to the Sustainable Development Goals (SDGs) we examine how bio-ecological remediation can be integrated into practice at scale.

The major production systems used today including earthen pond culture, closed-loop recirculating systems, marine cage culture, and aquaponics, and describe how artificial intelligence (AI)-enabled monitoring and decision-support tools are being layered onto these systems to improve water quality management, feeding efficiency, and disease surveillance. Because fish is a compact source of high-quality animal protein (approximately 20% protein by weight) along with essential amino acids, vitamins, and micronutrients, the choice of production system materially affects the nutritional value delivered to consumers.

A persistent constraint on scaling intensive freshwater aquaculture is the recurrence of bacterial infections and the ecological degradation organic loading, eutrophication, and loss of microbial balance" that predisposes ponds to disease outbreaks. We reaffirm that bio-ecological remediation, which uses microbial consortia, biofilters, phytoremediation, and integrated multi-trophic approaches to restore ecological equilibrium in culture environments, offers a scientifically grounded and economically viable pathway to sustainable intensification.

We further review a complementary tier of emerging strategies that include antimicrobial peptides, phage therapy, biosurfactants and bacteriocins, vaccination, phyto-therapeutics, nanotechnology-based diagnostics and remediation, and AI-driven disease diagnostics that act more directly on pathogens or host immunity while remaining compatible with ecological restoration goals. This review concludes with a research and policy agenda for mainstreaming bio-ecological remediation within India's freshwater aquaculture sector.

Keywords: Sustainable Aquaculture; Freshwater Fisheries; Bio-Ecological Remediation; Aquaponics; Economic Development

Introduction

Fish and other aquatic foods occupy a distinctive place in global food systems: they are nutrient-dense, relatively resource-efficient to produce compared with many terrestrial livestock systems, and central to the livelihoods of hundreds of millions of people worldwide, particularly in the Global South [1]. India ranks as the world's second-largest aquaculture producer and leads globally in inland fisheries [2], and inland aquaculture dominated by freshwater carp polyculture, but increasingly diversified into species such as pangasius, tilapia, and freshwater prawns now accounts for roughly 80–90% of the country's total aquaculture production [3]. Yet capture fisheries, both marine and inland, have plateaued or declined in many regions due to overfishing, habitat degradation, and climate variability, leaving aquaculture as the primary avenue through which India can meet rising per-capita fish demand.

This growth trajectory intersects with two global agendas. The first is the "blue economy" framework, which positions the sustainable use of aquatic resources as a driver of economic growth, employment, and ecosystem health rather than treating conservation and production as competing goals. The second is the Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), and SDG 14 (Life Below Water), all of which are directly implicated by how freshwater aquaculture is practiced. Aquaculture that is expanded without regard to ecological carrying capacity risks undermining the very water resources on which it depends, through organic enrichment, antibiotic overuse, and loss of biodiversity in and around culture systems. Against this backdrop, we previously reported on a state-level initiative in India aimed at using land-based and freshwater aquaculture as an engine of sustainable livelihood in Bihar, India. Initiated in 2014, we demonstrated the potential of restoring unproductive and waterlogged wastelands and converting them into productive fish-farming units. This approach addressed several constraints affecting community-based aquaculture, including poorly maintained ponds, siltation, limited technical knowledge, inadequate access to quality fish seed, and insufficient fisheries infrastructure. The initiative subsequently received global recognition through the World Bank Group's 2017 competition for innovative approaches addressing the Sustainable Development Goals [4]. This experience highlights the importance of integrating ecological restoration, scientific pond management, community participation, and appropriate technical support to improve the productivity and sustainability of freshwater aquaculture.

India's fisheries sector contributes substantially to national GDP, export earnings, and direct and indirect employment, with inland and freshwater aquaculture forming its fastest-growing segment. Fish consumption in India remains below global averages in many states, and demand is projected to rise with income growth and urbanization [5]. Because capture fisheries yield from rivers, lakes, reservoirs, and marine waters are constrained by ecological limits, the incremental fish supply required to meet this demand must come predominantly from aquaculture. In today's rapidly evolving agricultural landscape, achieving sustainability and productivity is no longer a choice, but a necessity. However, increasing intensification of aquaculture practices has resulted in the accumulation of organic matter, nitrogenous compounds, phosphorus, suspended solids, toxic metabolites, and microbial contaminants in culture systems. Excess feed, fecal matter, dead biomass, and metabolic wastes can increase ammonia, nitrite, nitrate, and phosphate concentrations, resulting in eutrophication, oxygen depletion, deterioration of sediment quality, and increased susceptibility of cultured organisms to disease [7]. The excessive use of chemical fertilizers and pesticides in conventional farming has stressed ecosystems, degraded soil health, and raised concerns over food safety and environmental degradation [8].

Freshwater aquaculture is particularly significant for food security because it can be practiced by smallholders using relatively modest capital namely a farm pond, seed stock, and basic feed inputs making it accessible to rural households that would otherwise have limited entry points into commercial food production. This is the logic underlying many state-level aquaculture promotion schemes in India, including the initiative referenced in this paper, which links pond-based freshwater aquaculture directly to poverty reduction objectives. However, the same accessibility that makes freshwater aquaculture attractive as a livelihood strategy also creates a management challenge: many new entrants to aquaculture lack the technical capacity to manage water quality, stocking density, and disease risk, which are the primary determinants of long-run pond productivity. This gap between accessibility and technical management capacity is precisely where bio-ecological remediation approaches, if properly extended to farmers, can have the greatest impact [4,9].

This review aims to provide a comprehensive assessment of bio-ecological remediation as a strategy for sustainable freshwater aquaculture, with particular emphasis on its economic, environmental, technological, and health-related dimensions. Specifically, the review summarizes the current evidence on the economic implications of bio-ecological remediation, compares major aquaculture production systems including pond culture, closed-loop/recirculating systems, marine aquaculture, and aquaponics with respect to their sustainability, productivity, and nutritional outputs, and examines the emerging role of artificial intelligence (AI)-enabled monitoring and management in optimizing water quality, resource use, and remediation processes. The review further characterizes the disease burden, particularly bacterial infections and associated antimicrobial resistance, as an important constraint to the sustainable intensification of freshwater aquaculture, while identifying key research, technological, and policy gaps that need to be addressed for the wider adoption and mainstreaming of bio-ecological remediation approaches. The review explains the emerging alternatives and adjunct therapeutic strategies (antimicrobial peptides, phage therapy, biosurfactants, bacteriocins, vaccination, phyto-therapeutics, nanotechnology, and AI-driven diagnostics) that complement bio-ecological remediation. These objectives are consistent with the need to integrate ecological management, precision aquaculture, disease control, and resource-efficient production to improve the long-term sustainability and resilience of freshwater aquaculture systems.

Methodology

This review employs a systematic approach to evaluate the ecological and economic outcomes of bio-ecological remediation in freshwater aquaculture, focusing on scaling sustainable practices to address food security and nutritional needs, particularly within the Indian context. A systematic literature search was conducted using online electronic databases for publications available between August 2020 and July 2026. The search was performed using three major databases: the National Center for Biotechnology Information (NCBI) *via* PubMed, Google Scholar, and ScienceDirect. The search strategy employed a combination of relevant keywords and phrases, including "aquaculture," "sustainable aquaculture," "Bio-ecological remediation," "pond management practices," "fish production regions, "aquaponics", "Economic development", "control strategies," "bio-ecological remediation challenges," and "prospects in India." Peer-reviewed journal articles, theses, conference proceedings, book chapters, project reports, and government publications were considered for inclusion. Retrieved records were initially screened based on their titles and abstracts. Articles considered potentially relevant were subsequently assessed through full-text evaluation. In addition, the reference lists of selected publications were manually screened to identify relevant studies that may not have been captured through the initial database searches. Key information, evidence, findings, and relevant messages were systematically extracted from the selected literature and incorporated into the review.

Aquaculture production systems

Aquaculture production systems encompass a range of farming approaches that differ in their water use, stocking density, resource inputs, environmental management, and technological intensity. These systems include conventional earthen ponds to recirculating aquaculture systems (RAS), integrated aquaculture, and aquaponics, all vary considerably in productivity, environmental footprint, disease risk, and potential for bio-ecological remediation.

Pond farming

Earthen pond culture remains the dominant freshwater aquaculture system in India, typically operated as extensive or semi-intensive polyculture of Indian and exotic carps, sometimes combined with freshwater prawns or air-breathing fish. Ponds function as semi-closed ecosystems where phytoplankton, zooplankton, benthic organisms, and the cultured fish interact continuously with pond water and sediment. Productivity depends on maintaining favorable dissolved oxygen, pH, ammonia, and organic load levels; when management lapses, self-pollution from uneaten feed and fish excreta drives eutrophication, oxygen depletion, and disease [10,11].

Closed-loop and recirculating aquaculture systems (RAS)

Closed-loop systems recirculate water through mechanical and biological filtration units, dramatically reducing water use and enabling high stocking densities in a controlled environment. RAS is capital- and energy-intensive relative to pond culture but offers superior control over water quality parameters and biosecurity, reducing (though not eliminating) disease risk [11,12]. RAS is increasingly viewed as a technology pathway for peri-urban and land-constrained aquaculture in India, particularly for high-value species.

Marine aquaculture

Marine cage culture and mariculture of finfish, shellfish, and seaweed represent a smaller but growing segment of India's aquaculture sector. While outside the primary freshwater focus of this paper, marine aquaculture shares many of the same ecological remediation challenges — nutrient loading beneath cages, benthic impacts, and disease transfer risk between farmed and wild populations and offers useful comparative lessons for freshwater practice.

Aquaponics

Aquaponics, the unification of hydroponics and aquaculture along with bio-ecological remediation strategies further suggests a reliable progression in efficient production of fish [13]. Aquaponics integrates recirculating fish culture with hydroponic plant production, using fish waste as a nutrient source for plants, which in turn help purify water returned to the fish tanks [14,15]. This tight biological coupling is itself a form of bio-ecological remediation embedded directly into system design and is considered an effective route for the phytoremediation of aquaculture wastewater [16], and aquaponics has attracted interest as a model for resource-efficient, near-zero-discharge food production for water- and land-constrained settings [16], although capital costs and technical complexity currently limit its uptake among small-holders.

The role of artificial intelligence

Across all four system types, AI-enabled tools are increasingly being layered onto conventional management practice [17,18]. Applications include sensor-based water quality monitoring with machine learning models (random forest, gradient boosting, neural networks, and ensemble classifiers) that predict dissolved oxygen fluctuations, ammonia spikes, or algal blooms before they become critical [19]. Computer vision and deep learning for automated fish counting, biomass estimation, growth tracking, and early behavioral detection of stress or disease [17,18,20]. Predictive feeding and effluent-treatment algorithms that optimize feed conversion ratios and support denitrifying/phosphorus-removing biological treatment, reducing both cost and the organic loading that drives eutrophication [21,22]. "IoT-integrated early-warning systems" that combine environmental, water quality, and historical epidemiological data to flag high-risk conditions in advance, with commercial platforms already demonstrating measurable gains in yield and cost efficiency [17]. AI does not substitute for ecological management but can substantially improve its precision and timeliness, allowing bio-ecological remediation interventions discussed later in Section 6) to be triggered proactively rather than reactively [19,21]. This involves the application of precision aquaculture technologies, including automated feeding devices, sensors to test the water quality, and use of artificial intelligence for real-time monitoring to augment fish production efficiency along with environmental management [22].

Nutritional value of farmed fish and the influence of production system

Fish is a nutrient-dense food, providing high-quality, readily digestible protein with a balanced profile of eight essential amino acids, and is a primary affordable protein source for hundreds of millions of people globally, contributing a substantial share of dietary animal protein intake in many countries [23].

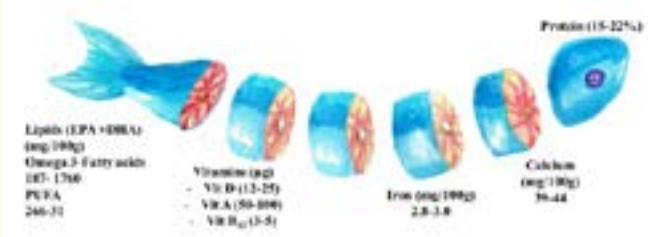


Figure 1: Illustrates the nutrients found in fish. EPA- eicosapentaenoic acid; DHA- docosahexaenoic acid. Values are from recent literature [Image is from creative commons].

The additionally rich sources of long-chain omega-3 polyunsaturated fatty acids (EPA and DHA) and micronutrients in aquatic species such as iodine, selenium, and zinc are represented in Fig.1. These are critical for cardiovascular, neurological, and immune function and are otherwise difficult to obtain in adequate quantities from plant-based diets alone [18,24]. This nutritional density is a key reason aquaculture is considered strategically important for addressing hidden hunger and micronutrient deficiency, not just caloric insufficiency [25].

The production system used has a measurable effect on the nutritional quality of the final product. Feed composition, stocking density, water quality, and stress levels all influence muscle

composition, fat content, and the retention of essential amino acids and fatty acids in farmed fish [24,25]. Table 1 give a comparative overview of the major freshwater-relevant aquaculture production systems used enlisting their typical stocking density and nutritional output. Fish raised in poorly managed, degraded pond environments are more prone to stress-related physiological changes and disease, which can compromise both yield and product quality, whereas well-managed systems including those supported by bio-ecological remediation tend to produce more consistent nutritional outcomes alongside higher survival rates [10,11].

System	Water use	Relative capital cost	Typical stocking density	Disease/biosecurity risk	Nutritional output consistency	Key Ref
Earthen pond culture	High (open water exchange)	Low	Low–moderate	High; vulnerable to self-pollution and *Aeromonas* outbreaks	Variable; strongly dependent on pond ecology	[10,11,26]
Closed-loop/ RAS	Very low (recirculated)	High	High	Moderate; controlled conditions, but high-density biosecurity failures can be severe	High and relatively consistent	[11,12,17]
Marine cage culture	Not applicable (open water)	Moderate–high	Moderate–high	Moderate; benthic loading and wild–farm pathogen transfer	Variable; species-dependent	[20,22]
Aquaponics	Very low (recirculated and coupled)	Moderate–high	Low–moderate (fish); intensive (plants)	Low–moderate; plant biofiltration can improve water quality	High for both fish and plant production	[14,15,16,27]

Table 1: Comparative overview of major freshwater-relevant aquaculture production systems.

Bacterial infections- a constraint on scaling

Bacterial disease is one of the most significant constraints on the sustainable intensification of freshwater aquaculture. Pathogens such as *Aeromonas hydrophila*, *Aeromonas veronii*, *Edwardsiella tarda*, and various **Vibrio** species associated with brackish and marine systems are opportunistic in nature: they proliferate when pond ecology is destabilized by high organic loading, poor water exchange, overstocking, and nutritional stress in the cultured animals [28]. In freshwater ponds specifically, motile *Aeromonad septicemia* (MAS) is among the most economically damaging recurring disease syndromes, capable of causing significant mortality events within days once triggered by a deterioration in water quality [29,30]; surveys of diseased freshwater fish have reported *A. hydrophila* infection prevalence in the range of 27–46%, with the large majority of isolates carrying one or more virulence genes (*aer*A (aerolysin gene), *hly*A (hemolysin gene), *act* (cytotoxic enterotoxin gene), *alt* (heat-labile cytotonic enterotoxin gene), *ast* (heat-stable cytotonic enterotoxin gene) [31].

The conventional response to bacterial disease outbreaks is therapeutic and, in poorly regulated contexts, prophylactic antibiotic use creates a secondary sustainability problem: the emergence of antimicrobial-resistant bacterial strains, residues in farmed fish that can affect export market access, and disruption of the pond's own beneficial microbial communities, which paradoxically increases vulnerability to future outbreaks [28]. Table 2 enlists the common bacterial pathogens and their associated diseases, their ecological trigger conditions and their reported

impact in freshwater aquaculture. Reported multiple-antibiotic-resistance (MAR) indices among *A. hydrophila* isolates from diseased fish frequently exceed the 0.2 threshold conventionally used to flag high-risk contamination sources, with resistance to commonly used antibiotics such as oxacillin, amoxicillin, and vancomycin observed in more than 70% of isolates in some regional surveys [32]. This creates a self-reinforcing cycle in which disease management inputs degrade the ecological conditions that would otherwise suppress disease.

Breaking this cycle requires addressing the underlying ecological drivers of pathogen proliferation rather than only treating outbreaks after they occur which is the central rationale for bio-ecological remediation [33,34]. Alternative and complementary disease-management strategies that have been investigated alongside ecological remediation include dietary probiotic supplementation [31,32], phyto-biotics and medicinal-herb-derived compounds [34], targeted anti-virulence compounds such as amentoflavone that block key toxins (e.g., aerolysin) without broadly suppressing bacterial populations [34], and bacteriophage- and antimicrobial-peptide-based approaches.

Pathogen	Associated disease	Ecological trigger conditions	Reported impact	Key Ref.
Aeromonas hydrophila	Motile Aeromonas septicemia (MAS), gastroenteritis, hemorrhagic septicemia	High organic load, poor water exchange, overstocking, thermal and nutritional stress	Infection prevalence of ~27–46% in surveyed outbreaks; high virulence-gene carriage and increasing multidrug resistance	[28,30-32]
Aeromonas veronii	Septicemia, ulcerative disease	Similar to *A. hydrophila*; opportunistic under degraded pond conditions	Frequently co-occurs with *A. hydrophila* in mixed infections	[28,30]
Edwardsiella tarda	Edwardsiellosis	Organic-rich sediment and low dissolved oxygen	Significant mortality in catfish and carp culture systems	[10,11]
Vibrio spp.	Vibriosis, particularly in brackish and marine-influenced systems	Salinity intrusion, nutrient loading, and elevated temperature	Economically important disease in cage and coastal pond aquaculture	[20,22]

Table 2: Common bacterial pathogens implicated in freshwater aquaculture disease outbreaks.

Bio-ecological remediation: Concept, mechanisms, applications, advantages, limitations, and future prospects

Bio-ecological remediation is the deliberate use of living organisms, microbial communities, and ecological engineering principles to restore and actively maintain the structural and functional integrity of an aquaculture environment, rather than to treat disease or pollution symptoms in isolation [39]. It differs from conventional environmental bioremediation which is typically a one-off cleanup of a contaminated site in that it is conceived as a *continuous, self-reinforcing management practice* integrated into the production cycle itself. The underlying premise is ecological: a freshwater pond, tank, or cage system is not simply a container for fish, but a functioning micro-ecosystem in which phytoplankton, zooplankton, benthic and planktonic microbial communities, sediment biogeochemistry, and the cultured animals are continuously interacting [1,2]. Productivity and disease resistance are emergent properties of that ecosystem's balance rather than of any single input.

With this perspective, bio-ecological remediation seeks to restore three interlinked forms of balance that intensive aquaculture tends to erode: (i) "microbial balance" that refers to a diverse, competitively stable microbiome in which opportunistic pathogens such as Aeromonas spp. cannot dominate [12,32]; (ii) "biogeochemical balance" that includes nutrient, oxygen, and redox cycling which prevents the organic and nitrogenous build-up which drives eutrophication and toxic ammonia/nitrite accumulation [11,12]; and (iii) "trophic balance" the flow of energy and waste between primary producers, consumers, and decomposers, so that no single trophic level accumulates an unsustainable nutrient load [11,20,41].

Mechanisms

Bio-ecological remediation is therefore best understood not as a single technology but as a design philosophy that can be implemented through several complementary mechanisms, described below. Table 3 describes the major bio-ecological remediation approaches, their mechanisms, applications, and reported benefits in aquaculture.

Microbial bioaugmentation and probiotic consortia

Beneficial bacterial strains (e.g., *Bacillus* spp., *Lactobacillus* spp., and photosynthetic bacteria) are introduced into pond water or incorporated into feed to competitively exclude pathogenic bacteria, break down organic waste, and support nitrogen cycling [31,32]. Mechanistically, this operates through resource and space competition, production of antimicrobial metabolites, and as discussed in Section 7.1, interference with pathogen quorum-sensing signaling, which suppresses virulence and biofilm formation without indiscriminately killing the wider microbial community [39]. Regular application of well-selected probiotic consortia has been associated with improved water quality parameters and reduced incidence of bacterial disease outbreaks in pond and tank trials, including protective effects against A. hydrophila-induced intestinal damage and mortality [31].

Biofiltration and nitrification–denitrification

Mechanical and biological filters, particularly relevant in RAS and aquaponic systems use nitrifying bacterial biofilms to convert toxic ammonia and nitrite into less harmful nitrate, maintaining water quality within safe thresholds for high-density culture [16,17]. In more advanced configurations, coupled nitrification–denitrification zones (aerobic biofilm layers paired with anoxic microsites) allow nitrate to be further reduced to nitrogen gas, achieving fuller nutrient removal rather than simple conversion. Continuous water-quality monitoring is considered essential to sustaining biofilter performance in RAS operations [17]. Beneficial bacterial strains (e.g., *Bacillus* spp., *Lactobacillus* spp., and photosynthetic bacteria) are introduced into pond water or incorporated into feed to competitively exclude pathogenic bacteria, break down organic waste, and support nitrogen cycling [31,32]. Regular application of well-selected probiotic consortia has been associated with improved water quality parameters and reduced incidence of bacterial disease outbreaks in pond and tank trials, including protective effects against *A. hydrophila*-induced intestinal damage and mortality [31,32].

Phytoremediation and constructed wetlands

Aquatic macrophytes and constructed wetland systems can be used to treat pond effluent before discharge or recirculation, removing excess nutrients, suspended solids, and some pathogens through plant uptake and rhizosphere microbial activity [34]. This approach is particularly relevant for reducing the environmental footprint of pond aquaculture clusters discharging into shared or ecologically sensitive water bodies [34].

Trophic level nutrient recycling: integrated multi-trophic aquaculture (IMTA) and biofloc technology

IMTA co-cultures species occupying different trophic levels (e.g., fish, filter-feeding mollusks, and algae or aquatic plants) so that the waste products of one species become a resource input for another, reducing net nutrient loading in the system as a whole [35]. Biofloc technology (BFT) which cultivates microbial consortia directly within the culture water to recycle nutrients into microbial protein while removing pollutants such as microplastics and heavy metals is a closely related approach with growing application beyond feed supplementation, into environmental remediation and circular-economy resource recovery [35]. While more established in marine and semi-intensive settings, both IMTA and BFT principles are increasingly being adapted to freshwater pond and cage systems [35].

Sediment and bottom soil bioaugmentation

Periodic pond bottom treatment liming, controlled drying, and application of bioremediating microbial products to sediment addresses the accumulation of organic matter and reduced (anaerobic) conditions at the pond bottom, which is a major reservoir for pathogenic bacteria between production cycles [36]. Restoring an aerobic, biologically active sediment layer accelerates organic matter turnover and reduces the release of hydrogen sulfide and ammonia from the pond floor.

Applications, advantages and future prospects

Bio-ecological remediation is applied across the aquaculture value chain: as prophylactic in-pond probiotic dosing and sediment

Remediation approach	Primary mechanism	Best-suited system(s)	Reported benefits	Key Ref.
Microbial bioaugmentation/probiotics	Competitive exclusion; quorum-sensing interference; organic waste breakdown; nitrogen cycling	Pond culture, RAS, hatchery systems	Reduced *A. hydrophila*-related mortality; improved growth and immune response	[31,32]
Biofiltration (nitrification–denitrification)	Bacterial biofilms Microbial nitrification Conversion of ammonia/nitrite to nitrate (and to N_2)	RAS, aquaponics	Improved and stabilized water quality under high stocking densities	[11,12]
Phytoremediation/constructed wetlands	Uptake of nutrients and suspended solids by macrophytes and rhizosphere microbiota	Pond-effluent treatment; cluster-level discharge management	Reduced nutrient loading and pollutant discharge to receiving water bodies	[34]
IMTA/biofloc technology	Cross-trophic nutrient recycling and microbial conversion of dissolved nutrients into biomass	Semi-intensive ponds, cage culture	Reduced net nutrient discharge and potential reduction in feed costs	[13,35]
Sediment/bottom management	Liming, pond drying, and bioaugmentation to improve sediment quality and microbial balance	Pond culture during inter-cycle periods	Reduced sediment-associated pathogen reservoirs and restored redox conditions	[10]

Table 3: Major bio-ecological remediation approaches, their mechanisms, applications, and reported benefits in aquaculture.

treatment in semi-intensive carp and prawn polyculture [1,2,32]; as a structural feature of RAS and aquaponic systems, where biofiltration and phytoremediation are built directly into system design [12,15]; as constructed wetlands and shared treatment ponds for cluster- and watershed-level effluent management [11,36]; as inter-cycle sediment bioaugmentation and controlled drying [11,42]; as AI-triggered precision dosing that responds to real-time water-quality signals rather than a fixed schedule [21,27,28]; and as a core component of poverty-focused livelihood programs, illustrated by our own state-level initiative [4,9]. These applications translate into tangible advantages: reduced antibiotic dependence and associated antimicrobial-resistance risk [18,20], lower recurring input costs once systems are established [1,2], improved yield stability through fewer sudden Aeromonad-driven mortality events [12,28], environmental co-benefits from reduced nitrogen, phosphorus, and organic discharge [35], alignment with circular-economy and nutrient-recycling goals [41], accessibility for resource-constrained smallholders given the low capital cost of core practices [4,5], and synergy with the adjunct therapeutic strategies discussed in Section 7 [32].

Limitations of bio-ecological remediation

These benefits are tempered by real constraints. Bio-ecological remediation acts more slowly than antibiotics and is unsuited as a stand-alone response to an acute, already-underway outbreak [8,22]; its efficacy is context- and species-specific, limiting transferability across regions [26,31]; it demands a level of technical literacy and monitoring capacity that many smallholders currently lack [4,5]; some approaches — biofiltration, constructed wetlands, IMTA/BFT — carry upfront infrastructure costs that can be prohibitive for the poorest farming households [7,9]; introducing external microbial strains carries a low but non-zero risk of instability or unintended ecological effects [26,32]; the field lacks standardized efficacy testing and quality certification [31,32]; and long-run, farm-level economic evidence remains thin [1,2]. Looking ahead, AI- and IoT-enabled precision remediation [16,20,22,24], genomics- and metagenomics-guided strain selection [26,27], convergence with nanotechnology-based diagnostics and remediation, synthetic biology-engineered consortia [27], standardization and certification frameworks

[31,32], cluster- and watershed-scale governance models [6,33], integration into climate-resilience planning [1,2], and deeper embedding within poverty-focused aquaculture programs [4,5] are all expected to expand the reach and reliability of bio-ecological remediation over the coming decade.

Emerging alternative and adjunct therapeutic strategies for bacterial disease management

Bio-ecological remediation restores the pond environment as a whole, but it is increasingly being paired with a second, complementary tier of strategies that act more directly on the pathogen or the host either by disrupting bacterial communication and virulence, delivering targeted antimicrobial or immunostimulatory molecules, or improving diagnostic speed and precision so that remediation and treatment can be triggered earlier [36]. These approaches share a common goal with bio-ecological remediation: reducing dependence on broad-spectrum antibiotics while preserving the beneficial microbial communities that ecological restoration works to build up. Table 5 summarizes the emerging alternatives and adjunct strategies for bacterial disease management and health monitoring in freshwater aquaculture.

Quorum-sensing inhibition and host-adversity strategies

Target specificity against pathogens can be achieved through quorum-sensing (QS) inhibition, which disrupts the chemical signaling bacteria use to coordinate virulence and biofilm formation, without disturbing beneficial microorganisms in the same environment. Host-adversity strategies, which make the host environment less favorable to pathogen colonization, offer a related approach. Naturally sourced quorum-sensing inhibitors (QSIs), together with the continued development of new QSI agents effective against resistant bacterial strains, represent a promising avenue for pathogen-specific control that is compatible with, rather than disruptive to, ecological remediation efforts [37].

Antimicrobial peptides (AMPs)

Antimicrobial peptides have emerged as a promising therapeutic class against fish pathogens. As small proteins, AMPs act either by modulating the fish immune system or by directly killing target pathogens [38]. *In vitro* and *in vivo* evaluation of synthetic and naturally derived AMPs has confirmed activity against a wide range of fish pathogens.

Phage therapy

Bacteriophage therapy uses a specific phage, or neo-phage cocktails, to maintain efficacy against multiple co-occurring infections while reducing the likelihood of bacterial resistance developing against any single agent [39]. Because phage survival is highly sensitive to environmental conditions, candidate phages must be rigorously tested for persistence under real pond and tank conditions before being deployed as a therapeutic or prophylactic tool.

Biosurfactants and bacteriocins

Biosurfactants (BS) are amphipathic biomolecules secreted by microorganisms that exhibit surface-active, multifunctional antifungal [39], antibacterial, and antiviral properties, and include peptides, acids, fatty acids, and polysaccharides. BS disrupt bacterial cell membranes and inhibit biofilm formation [40], while also acting as immunostimulants that strengthen the defense system of farmed fish against infection [41]. Bacteriocins "bioactive compounds produced ribosomally by bacteria such as **Bacillus** spp. and **Lactococcus** spp. [42] have emerged as eco-friendly alternatives to antibiotics in aquaculture. Their functions include acting as killing peptides, colonizing peptides, or signaling peptides capable of triggering the host immune system [42], with mechanisms of action including cell wall disruption and pore formation leading to rapid target-cell death; certain Gram-negative pathogens are inhibited through interference with RNA, DNA, and protein metabolism.

Vaccination

Vaccination is an effective active immunoprophylactic strategy for preventing disease outbreaks in aquaculture. Modern vaccines are being designed around modified subunits or whole inactivated organisms to target specific pathogens [42]. This global shift toward vaccination is being accelerated by advances in aquatic-animal vaccine technology, which are expected to be economically beneficial through reduced overall disease-management costs [43].

Phyto-therapeutics

Passive, plant-derived (phyto-therapeutic) approaches extract bioactive molecules from various plant sources to help farmed fish resist infection. Compounds such as diallyl tetrasulfide (allicin) and various essential oils have demonstrated broad-spectrum anti-parasitic and anti-fungal activity in aquaculture when delivered as

dietary supplements, complementing the medicinal-herb-based mitigation strategies already discussed in Section 5 [44].

Probiotic and prebiotic strain selection

Realizing the full benefit of probiotic and prebiotic interventions (Section 6.1) [32,34,35] depends on selecting well-adapted strains with established, species-specific benefits for growth and disease resistance, and on conducting regular microbial monitoring to confirm that beneficial strains remain dominant over time [40]. Selected strains should not adversely interact with other concurrent treatments. Because microbial populations can shift or mutate, new strains or combinatorial probiotic treatments should be developed on an ongoing basis, with dosing calibrated to environmental conditions, population size, and species dominance, and repeated at intervals sufficient to maintain a stable beneficial microbial community. Probiotic-based interventions have emerged as promising strategies for controlling fungal infections and mitigating mycotoxicosis in aquaculture systems and suppress the proliferation of pathogenic fungi and other potentially harmful microorganisms. Prebiotics include inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), resistant starch and they cause gut dysbiosis, cause intestinal barrier. The SCFA-producing bacteria include *Faecalibacterium*, *Roseburia*, *Bacteroides.* These beneficial microorganisms can enhance host immune defenses *via* TLR/NF-κB signalling, reduce systemic inflammation, improve water quality thereby contributing to improved fish health and sustainable aquaculture production [29].

Nanotechnology-based diagnostics and remediation

Nanotechnology is an emerging tool for both diagnosing disease and removing pollutants from aquaculture water bodies [45]. Miniaturization improves sensor precision and enables on-site testing and the large surface area characteristic of nanoparticles allows interaction with a greater number of target molecules, supporting proactive disease management and reduced economic losses. Molecular nanodiagnostic assays offer higher sensitivity, specificity, and precision than conventional pathogen-detection methods, and nanobiosensors are capable of detecting ultralow levels of both pathogens and pollutants in aquatic ecosystems [46]. Nano-remediation technologies including nanocatalytic oxidation, nanoadsorbents, nanofiltration, and real-time nanosensor monitoring show particular promise for addressing antibiotic pollution in aquaculture water bodies. On the therapeutic side, the ultralow size of nanoparticles allows them to overcome biological barriers, making them effective delivery vehicles for drugs, genes, or vaccines, and nanoparticles are increasingly used as vaccine adjuvants. Biopolymeric nanoparticles based on gelatin or chitosan are attractive vaccine-formulation options because they enhance antigen stability, protect antigens from enzymatic degradation, and allow sustained release [46]; a nano-based vaccine against **Vibrio anguillarum** has shown promising results [49]. Combinatorial nanoparticle-based delivery strategies can also simultaneously enhance immunogenicity against multiple pathogens [49]. Incorporating nanoparticles including phyto-based nanoparticles into feed formulations offers additional health benefits, boosting immune responses and supporting disease-preventive strategies in farmed fish.

Stem cell-based therapy

Stem cells possess the capacity for self-renewal and can generate new functional cells to replace damaged ones. Because they are multi-lineage, stem cells can support repair of damaged tissue, either by stimulating endogenous stem cell activity in a regulated manner or by replenishing the stem cell pool needed for tissue homeostasis and regeneration. While still an emerging area in aquaculture health management, stem cell-based approaches represent a longer-horizon strategy for strengthening farmed fish's intrinsic capacity to recover from injury and disease-related tissue damage.

Strategy	Primary mechanism	Examples/targets	Key advantage	Key Ref
Quorum-sensing inhibition (QSI)	Disrupts bacterial communication and virulence signaling	Natural and synthetic QS inhibitors	Pathogen-targeted approach with minimal disruption of beneficial microbiota	[43]
Antimicrobial peptides (AMPs)	Direct bacterial killing and/or immune modulation	*Y. ruckeri*, *Vibrio*, *Aeromonas*, *P. aeruginosa*, *Streptococcus*	Broad-spectrum activity with potentially lower resistance risk	[44-46,48]

Phage therapy	Specific bacteriophage-mediated bacterial lysis	Pathogen-specific or phage cocktails for mixed infections	High specificity and reduced impact on beneficial microbiota	[49,50]
Bio-surfactants	Membrane disruption, biofilm inhibition, and immune-stimulation	Peptides, fatty acids, and polysaccharides	Multifunctional antibacterial, antifungal, and antiviral potential	[41]
Bacteriocins	Cell-wall disruption, pore formation, and metabolic interference	Products from *Bacillus* and *Lactococcus* spp.	Eco-friendly potential alternative to conventional antibiotics	[47]
Vaccination	Active immune-prophylaxis using specific antigens	Subunit and whole-organism vaccines	Long-term protection and reduced disease-management costs	[49]
Phyto-therapeutics	Antimicrobial, antiparasitic, and immunomodulatory effects of plant bioactives	Allicin, essential oils, and medicinal herbs	Potential dietary delivery with relatively low ecological impact	[34]
Probiotic and prebiotic interventions	Modulation of the gut microbiota through beneficial microorganisms and fermentable substrates; restoration of microbial diversity, enhancement of short-chain fatty acid (SCFA) production, strengthening of intestinal barrier integrity, and regulation of host immune responses	Probiotics: *Lactobacillus*, *Bifidobacterium*, *Lactococcus*, *Saccharomyces boulardii;* Prebiotics: inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), resistant starch; Targets: gut dysbiosis, intestinal barrier, SCFA-producing bacteria, TLR/NF-κB signalling, systemic inflammation	Non-invasive microbiome-based approach that can improve gut microbial balance, barrier function, metabolic homeostasis, and host immunity; reduces pathogen colonization and disease-associated inflammation	[29]
Nanotechnology	Sensitive pathogen detection, targeted delivery, and pollutant removal	Nanobiosensors, nanoadsorbents, and nanovaccines	High sensitivity with diagnostic, therapeutic, and remediation applications	[45,46-48]
Stem cell-based approaches	Tissue repair and regenerative responses	Multilineage stem-cell approaches	Potential to enhance endogenous tissue recovery	[50]
AI-driven diagnostics	Image analysis, deep learning, and predictive modeling	Automated disease and behavioral detection	Early, non-invasive, and potentially cost-effective diagnosis	

Table 4: Emerging alternatives and adjunct strategies for bacterial disease management and health monitoring in freshwater aquaculture.

The existing literature suggests that bio-ecological remediation interventions can improve farm-level economics through several channels: reduced mortality and improved feed conversion, which lowers cost per unit of output [39,40]; reduced reliance on curative antibiotic treatment, which lowers input costs and market access risk given rising antimicrobial resistance in key pathogens [28,32]; and more stable year-on-year yields, which reduces income volatility for smallholder farmers [6,7]. Where remediation is adopted at a cluster or watershed level â€" rather than by individual farms in isolation â€" there is also evidence of positive spillover effects, since shared water bodies mean that one farm's pollution load affects neighboring farms' disease risk [7,33,32]. AI-enabled

effluent treatment and monitoring systems are further reported to improve the efficiency and adaptability of biological treatment processes relative to conventional fixed-protocol management, though the reviewed literature notes that data bottlenecks and implementation economics remain significant barriers to scaled deployment [16,12,13].

A multidimensional, non-antibiotic approach to disease management in aquaculture, particularly by targeting pathogens, improving host immunity, manipulating the aquatic microbiome, and enabling early diagnosis has been illustrated in Figure 2. The fish in the centre represents the diseased host, while the surrounding elements represent different bio-ecological, biological, therapeutic, and diagnostic interventions. The central cultured fish is surrounded by major groups of aquatic pathogens, including helminths, crustaceans, viruses, bacteria, protozoa, fungi, and algae [33,34]. This illustrates that aquaculture organisms are exposed to diverse infectious and parasitic agents, and that disease management therefore requires approaches beyond conventional antibiotics.

The one-health/ecological approach shown at the upper left emphasizes controlling disease by modifying the microbial and ecological environment rather than relying solely on direct antimicrobial treatment. Quorum quenching interferes with bacterial quorum-sensing signals, thereby reducing bacterial communication, biofilm formation, and expression of virulence factors. Prebiotics support the growth and activity of beneficial microorganisms, whereas probiotics introduce beneficial microorganisms that can compete with pathogens and improve host health. Postbiotics use beneficial microbial metabolites or components to reproduce some of the health-promoting effects of probiotics without necessarily introducing live microorganisms. Several biological and natural therapeutic approaches are shown around the fish (Figure 2). Phyto-therapeutics use plant-derived compounds and extracts with antimicrobial or immunomodulatory properties. Antimicrobial peptides and bacteriocins can directly inhibit or kill pathogenic microorganisms while potentially reducing dependence on conventional antibiotics. Biosurfactants can interfere with microbial membranes and biofilms and may also contribute to host immune stimulation. The lower portion highlights additional targeted approaches. Vaccines provide pathogen-specific preventive protection, while phage therapy uses bacteriophages to selectively infect and lyse bacterial pathogens. Stem-cell-based therapy represents a regenerative approach aimed at supporting tissue repair and recovery following disease or injury. On the right, nanotherapeutics and diagnostic/therapeutic technologies represent advanced technological approaches. Nanotechnology can facilitate sensitive pathogen detection and potentially enable targeted delivery of therapeutic agents. Diagnostic technologies support early identification of pathogens and disease, allowing intervention before outbreaks become severe.



Figure 2: Integrated bio-ecological and alternative strategies for disease management in aquaculture.

The figure illustrates the diverse pathogens affecting cultured fish, including bacteria, viruses, fungi, protozoa, helminths, crustaceans, and algae, and summarizes emerging approaches for their prevention and control. These include quorum-quenching strategies, prebiotics, probiotics, postbiotics, phyto-therapeutics, antimicrobial peptides, bacteriocins, biosurfactants, vaccines, phage therapy, nanotherapeutics, stem-cell-based approaches, and advanced diagnostic technologies. Together, these interventions can support pathogen control, microbiome stabilization, immune enhancement, early disease detection, and reduced dependence on conventional antimicrobial therapies, thereby contributing to more sustainable and ecologically balanced aquaculture systems**.**

AI-Driven diagnostics and predictive disease management

Beyond the water-quality and feeding applications discussed in Section 3.5, diagnostic-focused AI technologies enable precise pathogen detection that supports immediate, targeted treatment and helps prevent indiscriminate disease spread [42]. Informed, timely farm-level decisions are increasingly supported by AI-driven predictive models and real-time data collection [43]. Mechanized disease detection is now possible by combining image-processing and computer-vision technology [47], and AI-generated 3D imaging of diseased fish, built on optimized datasets and deep-learning-based data integration, can further enhance the accuracy of disease diagnosis [43]. These tools support early, accurate, non-invasive, real-time, and cost-effective diagnosis [43]. Nonetheless, variability in host pathogen interactions, the difficulty of interpreting heterogeneous field data, and the high economic cost of deployment remain significant challenges for these innovative diagnostic strategies.

Economic effects of bio-ecological remediation: Evidence and gaps

Existing literature suggests that bio-ecological remediation interventions can improve farm-level economics through several channels: reduced mortality and improved feed conversion, which lowers cost per unit of output [25,26]; reduced reliance on curative antibiotic treatment, which lowers input costs and market access risk given rising antimicrobial resistance in key pathogens [22,27]; and more stable year-on-year yields, which reduces income volatility for smallholder farmers [4,5]. Where remediation is adopted at a cluster or watershed level rather than by individual farms in isolation, there is also evidence of positive spillover effects, since shared water bodies mean that one farm's pollution load affects neighboring farms' disease risk [40,41]. The key evidence gaps and economic challenges in the adoption of bio-ecological remediation technologies for freshwater aquaculture are briefly discussed in Table 4. AI-enabled effluent treatment and monitoring systems are further reported to improve the efficiency and adaptability of biological treatment processes relative to conventional fixed-protocol management, though the reviewed literature notes that data bottlenecks and implementation economics remain significant barriers to scaled deployment [21,28]. However, several gaps constrain the current evidence base:

Evidence gap	Description	Implication	Key Ref
Limited long-term economic data	Most evidence comes from short production-cycle trials; multi-year data on cumulative returns in smallholder pond systems are scarce.	Farm-level investment decisions rely on incomplete cost–benefit evidence.	[25,26]
Heterogeneity of interventions	Bio-ecological remediation includes probiotics, biofiltration, phytoremediation, and IMTA/BFT, which are rarely compared directly under similar conditions.	Difficult to identify the most cost-effective option for a given aquaculture system.	[6,31,34]
Weak integration with extension systems	How small holders access, finance, understand, and correctly implement remediation technologies remains under-studied.	Adoption may lag behind demonstrated technical effectiveness.	[4,5]
Limited AI–remediation integration	AI-enabled monitoring is increasingly used for early detection, but economic evaluation of integrating it with automated remediation remains limited.	The true economic value of "smart" remediation systems remains uncertain.	[12,13,16]
Distributional and equity concerns	Benefits may disproportionately accrue to better-capitalized farmers.	Poverty-focused programs may not adequately reach the poorest farming households.	[4]

Table 5: Key evidence gaps and economic challenges in the adoption of bio-ecological remediation technologies for freshwater aquaculture.

Toward Practice: Lessons from a state-level freshwater aquaculture initiative

Our earlier reported initiative sought to use land-based and freshwater aquaculture as a livelihood and food-security intervention in an Indian state with a large population living below the poverty line, framed explicitly around the SDGs. Our earlier review provided a comprehensive overview of India's aquaculture sector, emphasizing its challenges, opportunities, and strategies for inclusive, sustainable development.

That experience underscores several practical implications for bio-ecological remediation programs seeking to operate at scale:

- **"Remediation must be low-cost and low-complexity at the point of use":** Smallholder farmers with limited working capital cannot absorb the cost or technical burden of sophisticated RAS-style biofiltration; probiotic application, sediment management, and simple constructed-wetland effluent treatment are more realistic entry points.
- **"Cluster-level coordination matters":** Since, pond water bodies are frequently interconnected or share a common water source, remediation adopted by isolated farms delivers weaker results than remediation coordinated across a farming cluster.
- **"Extension and training are as important as the technology itself"**: Farmers need practical, field-level guidance on recognizing early warning signs of ecological imbalance (unusual algal color, off-odors, erratic fish behavior) so that remediation can be applied proactively.
- **"AI-enabled monitoring can lower the technical literacy barrier":** By translating raw sensor data into simple actionable alerts that do not require farmers to interpret complex water chemistry themselves.

Policy and research agenda

Based on the evidence discussed in this review, several research and policy priorities emerge for advancing bio-ecological remediation in freshwater aquaculture. First, there is a need for multi-year, multi-site economic trials comparing specific remediation packages, including probiotic-only, biofiltration-only, and combined approaches, under comparable smallholder pond conditions, with standardized assessment of productivity, disease incidence, and net farm income. Second, research should focus on the development of low-cost, locally producible probiotic and bioremediation products to reduce dependence on imported or expensive commercial formulations that remain inaccessible to many small-scale farmers. Third, AI-based early-warning and decision-support systems should be integrated into public aquaculture extension services rather than being restricted to commercial or large-scale farms, thereby enabling resource-limited producers to benefit from advances in real-time water-quality monitoring and farm management. Fourth, cluster-level water-body management frameworks should be developed to facilitate shared environmental monitoring and coordinated remediation among farms that utilize common water resources or discharge into interconnected water bodies. Fifth, aquaculture development programs should incorporate explicit equity monitoring to assess whether bio-ecological remediation technologies are reaching economically vulnerable farming households targeted by state and national food-security initiatives, rather than primarily benefiting larger commercial operations. Finally, stronger integration between aquatic disease surveillance and antimicrobial stewardship policies is required, with greater emphasis on ecological management as a means of reducing disease pressure and dependence on antibiotics, thereby supporting public health, environmental sustainability, and continued access to domestic and international markets for Indian aquaculture products.

Conclusion

Freshwater aquaculture is central to India's food security and rural livelihood strategy, but its continued expansion is constrained by a recurring ecological problem: intensification degrades the very pond environments on which productivity depends, precipitating bacterial disease outbreaks that undermine both yields and farmer incomes. Bio-ecological remediation spanning probiotics, biofiltration, phytoremediation, and integrated multi-trophic approaches offers a scientifically credible pathway to break this cycle by restoring ecological balance rather than only treating disease after it emerges. When combined with AI-enabled monitoring and embedded within farmer-accessible extension systems, bio-ecological remediation has the potential to make freshwater aquaculture both more productive and more sustainable, supporting India's broader goals for poverty reduction, nutrition security, and progress against the SDGs. Realizing this potential, however, will require addressing substantial evidence gaps concerning the long-term economics, comparative

effectiveness, and equitable and accessible implementation of these technologies—priorities that this review seeks to define as a future research and policy agenda.

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Conceptualization, AS & AKV; methodology, AV, ArV & AKV; validation, AS & AV; formal analysis, AS, ArV & AKV; investigation, ArV & AKV, writing-original draft preparation, AS, AV & ArV; writing-review and editing AS, ArV & AKV.

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Conflicts of Interest

The authors declare no conflict of interest.

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