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Emerging and Novel Approaches in Aquaculture: A Pathway Toward Sustainable Intensification

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ABSTRACT

The rapid expansion of aquaculture as the primary driver of global seafood production necessitates a paradigm shift toward sustainable intensification. Traditional production systems, while economically effective, face mounting challenges related to water scarcity, environmental nutrient loading, disease outbreaks, and climate vulnerability. This manuscript presents a comprehensive synthesis of emerging technological innovations that are reshaping contemporary aquaculture practices. Key advances examined include recirculating aquaculture systems enhanced with artificial intelligence and microalgae integration, biofloc technology for improved water quality and immune modulation, anaerobic ammonium oxidation (anammox) and complete ammonia oxidation (comammox) processes for energy-efficient nitrogen removal, nanotechnology applications for targeted drug delivery and water treatment, advanced oxidation processes (AOPs) and electrochemical methods for recalcitrant pollutant degradation, bioencapsulated oral vaccines for non-invasive disease prevention, integrated multitrophic systems grounded in circular economy principles, and biochar-based filtration for nutrient recovery and contaminant adsorption. Drawing upon recent engineering, biological, and materials science literature, this review critically evaluates the mechanistic foundations, operational performance, scalability constraints, and economic viability of these approaches. The synthesis reveals that while individual technologies offer substantial improvements in water efficiency, waste reduction, and disease control, their optimal implementation increasingly depends on hybrid configurations that combine complementary innovations. Furthermore, the integration of automation, real-time sensing, and data-driven decision support is transforming aquaculture into a precision production system. However, significant barriers remain, including high capital requirements, technical complexity, and the need for context-specific adaptation, particularly in resource-limited settings. Future research priorities include the development of low-cost modular systems, standardized operational protocols, and policy frameworks that incentivize the adoption of circular, low-carbon production models.

Keywords: **Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Anammox, Comammox, Advanced Oxidation Processes (AOPs), Biochar**

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1. Introduction

Global aquatic animal production has experienced unprecedented growth over the past four decades, with aquaculture now contributing over 59% of total fisheries production and projected to reach 111 million tonnes by 2032 [1]. This expansion reflects both the stagnation of wild capture fisheries and the increasing recognition of aquatic foods as essential components of food security, nutrition, and livelihoods worldwide. Per capita seafood consumption has risen from 9.0 kg in 1961 to more than 20 kg in recent years, driven by population growth, rising incomes, and shifting dietary preferences toward lean protein sources [2].

However, the intensification of aquaculture has generated significant environmental and biological challenges that threaten long-term sustainability. Conventional production systems, including pond cultures, cage farms, and flow-through raceways, typically operate as open systems with substantial water exchange. This design results in the discharge of nutrient-rich effluents that contribute to eutrophication, harmful algal blooms, and benthic degradation. Quantitative analyses indicate that conventional systems lose approximately

45% of feed nitrogen and 60% of feed phosphorus to the surrounding environment [1]. Concurrently, the accumulation of organic matter in pond sediments can trap 80% of carbon and nitrogen inputs, highlighting the magnitude of unutilized resources [2].

Water scarcity represents another critical constraint. Freshwater resources are increasingly allocated among agricultural, industrial, and domestic uses, limiting availability for aquaculture expansion [3]. Climate change exacerbates this pressure through altered hydrological patterns, rising water temperatures, and increased frequency of extreme weather events [4]. Moreover, disease outbreaks in intensive production settings cause substantial economic losses, estimated at billions of dollars annually, and have driven the widespread use of antibiotics, raising concerns about antimicrobial resistance and food safety [5].

These interconnected challenges have motivated the development and adoption of novel technologies designed to decouple aquaculture production from environmental degradation while maintaining or improving economic performance [6]. This review examines emerging approaches across four domains: engineered production systems that minimize water use and manage waste internally; biological innovations that enhance system resilience through microbial community management; nanotechnological and electrochemical applications that enable targeted water treatment and pollutant degradation; and integrated production models that transform waste streams into valuable co-products [7].

2. Recirculating Aquaculture Systems: Engineering Advances and Intelligent Integration

Recirculating aquaculture systems (RAS) represent a fundamental departure from traditional open production models. In RAS, water is continuously treated and reused within a closed loop, reducing freshwater consumption by 90-99% compared to flow-through or pond systems [8]. The core treatment train typically includes solids removal, biological filtration, degassing, oxygenation, and disinfection, with only a small fraction of system water discharged as sludge or effluent [9]. This design enables high-density production in controlled environments, independent of external water bodies and climatic conditions [8].

Recent engineering advances have substantially improved RAS performance across multiple dimensions. Innovations in tank hydrodynamics and geometry have demonstrated that octagonal tank configurations improve flow uniformity and waste transport compared to traditional rectangular or circular designs, reducing stagnant zones and enhancing self-cleaning capacity [9]. Low-head oxygenation systems have reduced energy consumption for dissolved oxygen management by 20-40% while maintaining supersaturated conditions necessary for high-density culture [10]. Modular biofilter designs incorporating moving bed bioreactors with optimized carrier media have increased nitrification efficiency and reduced footprint requirements [11].

Perhaps most transformative has been the integration of automation and artificial intelligence (AI) into RAS management. Because closed systems generate continuous data streams from sensors monitoring dissolved oxygen, pH, temperature, ammonia, nitrite, nitrate, and other parameters, they are uniquely suited to data-driven decision support [10]. Machine learning algorithms applied to these data can predict water quality deterioration before critical thresholds are reached, optimize feeding schedules based on real-time consumption patterns, and detect anomalous conditions indicative of system failure or disease onset [11]. AI-driven feeding systems have achieved 15-20% improvements in feed conversion ratios while reducing labor requirements by 25-30% [10].

The integration of microalgae cultivation into RAS represents an emerging frontier with substantial promise for nutrient recycling and waste valorization. Microalgae assimilate dissolved inorganic nitrogen and phosphorus from RAS effluent, converting these waste products into algal biomass that can be harvested and processed into feed ingredients, biofertilizers, or biofuel feedstocks [12]. Experimental systems have achieved 60-90% nutrient removal efficiency while simultaneously producing oxygen through photosynthesis, reducing aeration requirements [13]. This approach transforms RAS from a waste-generating system to a circular production model where effluents become inputs for secondary production [8].

Despite these advances, RAS adoption faces persistent barriers. Capital costs for commercial-scale systems remain substantial, often exceeding $10-15 per kilogram of annual production capacity, which limits accessibility for small and medium enterprises [9]. Energy intensity, driven primarily by pumping, aeration, and temperature control, creates operating costs that can exceed those of pond culture by 30-50% [11]. Off-flavor compounds, particularly geosmin and 2-methylisoborneol produced by certain bacteria, accumulate in RAS and require purging periods of 5-10 days in clean water before harvest, adding 5-7% to production costs [12]. Addressing these limitations through continued engineering innovation remains a priority.

3. Biofloc Technology and Advanced Nitrogen Removal: Anammox and Comammox

Biofloc technology (BFT) offers an alternative approach to sustainable intensification that leverages microbial community management rather than mechanical filtration. In BFT systems, minimal water exchange is combined with carbon supplementation to maintain a high carbon-to-nitrogen ratio, typically 10:1 to 20:1, which promotes the growth of heterotrophic bacteria [14]. These bacteria assimilate ammonia directly into microbial biomass, reducing reliance on autotrophic nitrification and its associated lag periods [15]. The resulting microbial aggregates, known as bioflocs, consist of bacteria, microalgae, protozoa, and organic matter bound together by extracellular polymeric substances [14].

Comparative evaluations of BFT and RAS have revealed distinct performance characteristics. In a controlled trial with pacu (Piaractus mesopotamicus) juveniles, BFT achieved superior water quality outcomes, with nitrite concentrations of 0.27 mg/L compared to 0.64 mg/L in RAS, while total ammoniacal nitrogen levels remained similar [15]. Growth performance was significantly enhanced in BFT, with improved weight gain, specific growth rate, and feed conversion ratio. Notably, renal expression of interleukin-1β (il-1β), a key pro-inflammatory cytokine involved in innate immune responses, was significantly higher in fish reared in BFT, suggesting that biofloc microorganisms provide immunostimulatory effects [15]. Recent advances in nitrogen cycle microbiology have introduced anaerobic ammonium oxidation (anammox) and complete ammonia oxidation (comammox) as transformative processes for nitrogen management in intensive aquaculture [25]. Anammox bacteria belonging to the phylum Planctomycetota directly convert ammonium and nitrite to dinitrogen gas under anoxic conditions, eliminating the need for organic carbon supplementation required by conventional denitrification [26]. In anammox-based systems, approximately 50% of the oxygen demand and 100% of the organic carbon demand for nitrogen removal are eliminated compared to nitrification-denitrification processes, reducing operational costs by 30-40% [25]. Pilot-scale anammox reactors integrated with RAS have achieved nitrogen removal rates of 0.5-1.2 kg N/m^3/day while producing negligible nitrous oxide, a potent greenhouse gas [26].

Comammox bacteria (e.g., Nitrospira inopinata) represent an even more recent discovery, capable of oxidizing ammonia directly to nitrate in a single organism [27]. This complete nitrification pathway shortens the two-step nitrification process and reduces intermediate nitrite accumulation, which is toxic to aquatic animals [25]. Metagenomic surveys of commercial RAS biofilters have revealed that comammox organisms constitute 10-30% of the ammonia-oxidizing community in systems with low ammonium concentrations (below 1 mg/L), suggesting their ecological niche in well-managed aquaculture [27]. Unlike anammox, comammox requires oxygen but produces no nitrous oxide, and its cellular yield is approximately 2.5 times higher than canonical ammonia-oxidizing bacteria, enabling stable biomass retention in biofilters [26].

The mechanistic basis for these effects involves multiple pathways. Bioflocs serve as supplemental feed sources, providing high-quality protein, lipids, vitamins, and minerals that contribute to nutritional requirements [16]. The microbial community produces exoenzymes that break down complex organic compounds, making nutrients more available. Certain bacteria within bioflocs synthesize polyhydroxyalkanoates, short-chain fatty acids, and other metabolites with prebiotic and immunomodulatory properties [17]. Additionally, competitive exclusion by beneficial microorganisms may suppress opportunistic pathogens, contributing to disease resistance [14].

Recent innovations have extended BFT applications to marine systems through the integration of ultrafiltration (UF) membranes. A combined BFT-UF process successfully established simultaneous nitrification and denitrification in marine RAS, achieving rapid start-up of denitrification within 24 hours through the introduction of polyhydroxyalkanoates as a carbon source [18]. This configuration achieved 100% removal of potential pathogens, including Vibrio and Tenacibaculum species, while maintaining stable operation for 180 days. The coexistence of ammonia-oxidizing archaea and denitrifying bacteria synergistically promoted simultaneous nitrogen removal, demonstrating the potential for intensified nutrient management

[18]. Hybrid anammox-biofloc systems have recently demonstrated total nitrogen removal exceeding 90% while reducing biofloc suspended solids by 40% compared to conventional BFT, addressing two major limitations simultaneously [27].

However, BFT implementation requires careful management of several parameters. Total suspended solids accumulate over time and must be controlled through settling or filtration to prevent gill irritation and oxygen depletion [16]. Alkalinity supplementation is typically necessary to maintain pH stability, as both nitrification and heterotrophic growth consume alkalinity. System start-up requires 2-4 weeks for microbial community establishment, during which water quality must be carefully monitored [15]. For anammox and comammox systems, longer start-up periods of 6-12 weeks are typical, and both processes are highly sensitive to temperature fluctuations and dissolved oxygen concentrations below 0.5 mg/L or above 2.0 mg/L, respectively [25,26]. These management requirements create technical barriers that may limit adoption in settings with limited operational expertise [17].

4. Nanotechnology and Advanced Oxidation Processes (AOPs): Targeted Interventions for Health and Water Quality

Nanotechnology has emerged as a versatile platform for developing targeted interventions in aquaculture, spanning disease management, water treatment, and nutrition. Nanoparticles, defined as materials with at least one dimension between 1 and 100 nanometers, exhibit unique physicochemical properties including high surface-area-to-volume ratios, quantum effects, and enhanced reactivity that enable applications not possible with conventional materials [19]. A comprehensive review of nanotechnological applications in modern aquaculture has documented over 200 distinct nanoparticle formulations developed for aquatic species [19].

In disease management, nanoparticle-based delivery systems offer substantial advantages over conventional therapeutics. Metallic nanoparticles, particularly silver and copper nanoparticles, exhibit broad-spectrum antimicrobial activity through multiple mechanisms including membrane disruption, reactive oxygen species generation, and interference with electron transport chains [20]. When incorporated into aquaculture systems, these nanoparticles can reduce bacterial loads in water without the selective pressure associated with antibiotic use. Moreover, nanoparticle encapsulation of antibiotics can improve bioavailability, reduce required doses, and enable targeted delivery to sites of infection [19].

Water treatment represents another promising application domain. Nanofiltration membranes with pore sizes below 10 nanometers can remove viruses, dissolved organic compounds, and multivalent ions from recirculating water, complementing conventional biological and mechanical treatment [20]. Advanced oxidation processes (AOPs), including electrochemical oxidation, photocatalysis, and ozonation, have gained particular attention for degrading recalcitrant organic pollutants that resist conventional biological treatment [28]. Electrochemical AOPs generate hydroxyl radicals (•OH) at the surface of dimensionally stable anodes (e.g., boron-doped diamond or mixed metal oxides), which non-selectively oxidize antibiotics, pesticides, off-flavor compounds, and microplastics [29]. A recent study demonstrated that electrochemically generated hydroxyl radicals achieved 95% removal of oxytetracycline and 85% mineralization of total organic carbon in RAS effluent within 60 minutes, with energy consumption of 0.8 kWh/m^3 [28].

Photocatalytic nanoparticles, particularly titanium dioxide (TiO_2), generate reactive oxygen species upon ultraviolet illumination that degrade organic pollutants including antibiotics, pesticides, and off-flavor compounds. Advanced oxidation processes incorporating photocatalytic nanoparticles have demonstrated effectiveness in controlling geosmin and 2-methylisoborneol, addressing a persistent challenge in RAS product quality [21]. Electro-Fenton processes, which combine electrochemical iron dissolution with hydrogen peroxide generation, have achieved 99% removal of sulfadiazine and 70% removal of antibiotic resistance genes from aquaculture wastewater, with the added benefit of in-situ iron recycling [29].

Nutritional applications of nanotechnology include the development of nano-encapsulated vitamins, minerals, and fatty acids with enhanced stability and bioavailability. Conventional feed supplementation often requires excessive dosing to compensate for degradation during processing, storage, and gastrointestinal passage [19]. Nanoencapsulation protects sensitive compounds from oxidation and enzymatic digestion, enabling precise delivery to absorption sites. Selenium nanoparticles, for example, have shown superior bioavailability and antioxidant activity compared to conventional selenium sources, with lower toxicity risks [20]. Nevertheless, the demonstrated efficacy and scalability of this approach suggest substantial potential for commercial adoption, particularly for high-value species where disease losses represent significant economic impacts [22]. Despite these promising applications, nanotechnology and AOPs in aquaculture face significant challenges. Regulatory frameworks for nanomaterial and electrochemical treatment use in food-producing animals remain underdeveloped in many jurisdictions, creating uncertainty for commercial adoption [21]. Environmental fate and toxicity of nanomaterials and AOP byproducts released from aquaculture operations are incompletely characterized, with concerns about persistence, bioaccumulation, and ecosystem effects [28]. Production costs for nanomaterials and the energy requirements for electrochemical AOPs (typically 0.5-2.0 kWh/m³) remain substantial [29]. Addressing these gaps through targeted research and regulatory development is essential for responsible implementation [19].

5. Oral Vaccination Through Bioencapsulation: A Paradigm Shift in Disease Prevention

Disease outbreaks represent a primary constraint on aquaculture intensification, with global losses estimated at $6-10 billion annually [5]. Conventional disease management has relied heavily on antibiotic therapy, but growing concerns about antimicrobial resistance, regulatory restrictions on antibiotic use, and consumer demand for antibiotic-free products have driven interest in preventive approaches, particularly vaccination [22].

Injectable vaccines, while effective for many bacterial and viral diseases, present practical limitations in aquaculture. Individual handling and injection are labor-intensive, stressful for fish, and impractical for small fish below a certain size threshold [22]. Mortalities from handling stress during vaccination can offset disease prevention benefits. Immersion vaccines, while less labor-intensive, require high antigen doses and provide relatively short duration of protection. These limitations have motivated the development of oral vaccines that can be administered through feed, eliminating handling stress and enabling mass vaccination [23].

Recent advances in bioencapsulation technology have overcome traditional barriers to oral vaccination, including antigen degradation in the gastrointestinal tract and insufficient immune stimulation. In a pioneering study, researchers genetically modified the microalga Nannochloropsis sp. to produce a protective protein from Vibrio harveyi, a bacterial pathogen responsible for vibriosis [23]. These modified microalgae were then fed to Artemia, small crustaceans that naturally consume microalgae and serve as live feed for larval and juvenile fish. Fish consuming Artemia containing the vaccine antigen mounted protective immune responses, achieving 100% survival following challenge with virulent V. harveyi, compared to 40% survival in non-vaccinated controls [23].

This bioencapsulation approach offers several advantages over conventional oral vaccine delivery. The microalgal cell wall provides natural protection against gastric degradation, ensuring antigen delivery to the distal intestine where immune induction occurs [24]. Antigen expression in microalgae can be scaled through conventional photobioreactor cultivation, providing a low-cost production platform. Incorporation of the vaccine into the natural food chain eliminates the need for specialized feed manufacturing or dosing equipment. Moreover, the approach is compatible with combination vaccines expressing multiple antigens from a single microalgal strain [23].

Current limitations include the high upfront costs of developing genetically modified microalgal strains, regulatory requirements for genetically modified organism use in food production, and the need for consistent antigen dosing across heterogeneous feeding behavior [24]. Ensuring that all fish consume sufficient quantities of bioencapsulated vaccine while avoiding over-dosing remains a practical challenge, particularly in large production units with variable feeding activity.

6. Circular Economy Models: Integrated Multi-Trophic Aquaculture, Biochar, and Nutrient Recycling

The concept of circular economy, which emphasizes waste prevention, resource efficiency, and material recycling, has gained substantial traction in aquaculture research and policy [1]. Integrated multi-trophic aquaculture (IMTA) represents a practical implementation of circular principles, combining fed species (finfish or shrimp) with extractive species that utilize waste outputs as growth inputs [6]. Typical IMTA configurations include seaweeds or microalgae that assimilate dissolved inorganic nutrients, and suspension-feeding bivalves or deposit-feeding echinoderms that remove particulate organic matter [7].

Quantitative assessments of IMTA performance have demonstrated substantial reductions in net nutrient discharge. In systems combining finfish with seaweed and shellfish, nitrogen removal of 40-60% and phosphorus removal of 30-50% have been reported, with corresponding reductions in biochemical oxygen demand and suspended solids [1]. These efficiencies translate directly to environmental benefits, including reduced eutrophication risk and benthic impacts. Additionally, the production of extractive species provides diversified revenue streams that can improve overall farm profitability and risk management [6].

Biochar, a carbon-rich material produced through pyrolysis of biomass residues, has emerged as a complementary circular economy technology for aquaculture nutrient recovery and water treatment [30]. Produced from aquaculture waste solids, agricultural residues, or forestry byproducts at temperatures ranging from 350-700°C, biochar exhibits high porosity (specific surface area typically 200-800 m^2/g), cation exchange capacity, and surface functional groups that adsorb ammonium, phosphate, heavy metals, and organic contaminants [31]. When incorporated into RAS or IMTA systems, biochar filters have achieved ammonium adsorption capacities of 15-45 mg/g and phosphate adsorption of 10-30 mg/g, depending on feedstock and pyrolysis conditions [30].

The dual role of biochar as both a filtration medium and a soil amendment creates closed-loop nutrient pathways [32]. Nutrient-laden biochar recovered from aquaculture systems can be applied to agricultural soils as a slow-release fertilizer, improving soil carbon stocks, water-holding capacity, and crop yields while sequestering carbon for centuries [31]. Life cycle assessment of biochar-integrated aquaculture has demonstrated net greenhouse gas reductions of 1.5-3.0 kg CO_2-equivalent per kg of biochar produced, with additional benefits from avoided synthetic fertilizer production [30]. Furthermore, biochar supports beneficial microbial biofilms, functioning as a carrier for nitrifying and anammox bacteria in biofilters, with recent studies showing 25% higher nitrogen removal rates compared to conventional plastic carriers [32].

Recent projects have demonstrated the practical feasibility of circular aquaculture models in commercial settings. A project implemented in Vietnam's Mekong Delta successfully piloted zero-discharge shrimp production using recirculating systems combined with waste transformation technologies [3]. Circular feed solutions, derived from biotransformed aquaculture waste, reduced input feed costs by up to 50% while decreasing dependence on imported feed ingredients that account for 70% of production costs in intensive systems. On-site biochar production from shrimp pond sludge reduced solid waste volume by 70% and generated a co-product valued at $200-400 per ton, improving overall farm profitability by approximately 35% [3,32].

Integration of seaweed and microalgae cultivation into circular systems offers additional benefits beyond nutrient recovery. Seaweeds provide habitat structure that reduces stress in co-cultured animals and can buffer water temperature fluctuations [7]. Microalgae produced from nutrient waste streams command market values three times higher than seaweeds, providing high-value co-products that improve system economics [3]. Moreover, both seaweeds and microalgae contribute to carbon sequestration, supporting climate mitigation objectives while generating carbon credits [6]. Biochar produced from harvested seaweed or microalgal biomass following nutrient extraction achieves even higher adsorption capacities (up to 60 mg/g for ammonium) due to the high ash and polysaccharide content of these feedstocks [30].

Scaling these circular models presents challenges related to system complexity and management requirements. IMTA requires balanced production ratios among fed and extractive species to avoid nutrient limitation or excessive accumulation, which necessitates careful design based on nutrient mass balance calculations [1]. Biochar production requires pyrolysis equipment and temperature control systems that represent capital investments of $10,000-50,000 for farm-scale units, and biochar regeneration (nutrient desorption) typically requires chemical treatment with acids or bases, generating secondary waste streams [31]. Market development for extractive species, particularly seaweeds and microalgae, is often less advanced than for conventional finfish and shrimp, requiring parallel investments in value chain development [7]. Additionally, regulatory frameworks in many jurisdictions do not yet accommodate integrated production systems or on-farm biochar production, creating permitting and compliance barriers [3].

7. Genetic Improvement and Biomarker Development for Health Resilience

Genetic selection for disease resistance represents a complementary approach to environmental management and vaccination for disease control [4]. Selectively bred lines with enhanced resistance to specific pathogens have been developed for several commercially important species, with documented reductions in disease losses of 20-50%. The U.S. Department of Agriculture Agricultural Research Service has developed rainbow trout lines with resistance to bacterial cold water disease (Flavobacterium psychrophilum) and columnaris disease (Flavobacterium columnare), with the double-resistant line currently undergoing on-farm evaluation [4].

The integration of biomarker discovery with genetic improvement programs offers opportunities to accelerate selection progress and enable non-invasive health assessment [5]. Biomarkers, including gene expression profiles, protein signatures, and metabolite patterns, can indicate disease susceptibility or immune status before clinical signs appear. Recent research has identified candidate biomarkers for columnaris disease resistance in rainbow trout, including immune-related genes differentially expressed between resistant and susceptible lines. Validation of these biomarkers across production environments and life stages is ongoing [5].

Microbiome characterization has emerged as another frontier in health management, recognizing that the microbial communities associated with farmed fish and their production environment profoundly influence disease susceptibility [24]. Comparative studies of resistant and susceptible genetic lines have revealed differences in gut microbiota composition that may contribute to resistance mechanisms. Isolation of commensal bacteria more abundant in resistant fish enables evaluation of their protective effects when administered as probiotics, potentially providing an alternative to conventional disease control [4].

These genetic and genomic approaches share the advantage of providing durable, non-chemical disease management once implemented [5]. However, they require substantial upfront investment in breeding infrastructure, phenotyping capacity, and molecular tools that may be unavailable in many production settings. Moreover, the specificity of resistance to particular pathogen strains means that genetic protection may be circumvented by strain variation, necessitating ongoing monitoring and potential line replacement [4].

8. Challenges, Integration Pathways, and Future Directions

The technological innovations reviewed here, while individually promising, face common barriers to widespread adoption. Capital costs for advanced systems, particularly RAS, AOPs, and biochar pyrolysis units, remain substantial and may exceed economic returns in lower-value commodity production [11,29,31]. Technical complexity creates dependence on specialized expertise for system design, operation, and troubleshooting, limiting applicability in settings with limited technical capacity [10]. Regulatory frameworks have lagged behind technological development, creating uncertainty for commercial implementation of genetically modified organisms, nanomaterials, anammox/comammox cultures, and novel waste treatment processes [21,25].

Recognizing these barriers, recent research has emphasized integration pathways that combine complementary technologies to address multiple constraints simultaneously [12]. Hybrid RAS-BFT configurations combine the process control of mechanical systems with the biological water treatment and immunostimulation of biofloc communities [18]. Integration of anammox or comammox with BFT or RAS reduces nitrogen removal energy costs by 30-50% while minimizing sludge production [26,27]. Combination of microalgae cultivation with RAS or BFT addresses nutrient accumulation while producing valuable co-products that improve system economics [13]. Nanotechnology-enabled water treatment can be combined with bioencapsulated vaccine delivery to address both environmental and health challenges within an integrated management framework [21,23]. Electrochemical AOPs coupled with biochar filtration achieve sequential degradation of recalcitrant pollutants and polishing adsorption of residual organics and metals, with synergistic effects that reduce energy consumption by 25-40% compared to AOPs alone [28,30]. Precision aquaculture, enabled by real-time sensing, data analytics, and automated control, provides an overarching framework for technology integration [11]. By continuously monitoring key parameters (including ammonium, nitrite, nitrate, pH, dissolved oxygen, temperature, and oxidation-reduction potential) and adjusting system operations in response to changing conditions, precision management can optimize performance while minimizing resource inputs and waste outputs [10]. Machine learning algorithms applied to sensor data have demonstrated predictive capabilities for water quality deterioration, disease outbreaks, and off-flavor accumulation, enabling proactive rather than reactive management [11]. Real-time control of anammox and comammox reactors using dissolved oxygen and conductivity sensors has improved nitrogen removal stability by 40% and reduced start-up failures by 60% [26]. As sensor costs decline and analytical tools improve, precision approaches will become increasingly accessible [12].

Looking forward, several research priorities emerge from this synthesis. First, development of low-cost, modular system designs that reduce capital barriers and enable incremental adoption, particularly in resource-limited settings [3]. Second, standardization of operational protocols and performance metrics for emerging biotechnologies (anammox, comammox) and physicochemical treatments (AOPs, biochar) to facilitate technology transfer and comparative evaluation across systems and species [8,25,29]. Third, life cycle assessment and techno-economic analysis to quantify environmental and economic trade-offs and guide technology selection for specific contexts [1]. Fourth, policy development that incentivizes circular, low-carbon production models while ensuring food safety, environmental protection, and social equity [7]. Fifth, research on combined pollutant removal (nutrients, antibiotics, microplastics, and pathogens) using hybrid AOP-biochar-nanofiltration systems to address the multi-contaminant reality of aquaculture effluents [28,30,32].

9. Conclusion

The global aquaculture sector stands at a critical juncture, where continued expansion on conventional trajectories threatens environmental sustainability while intensifying pressures from water scarcity, disease, and climate change. The emerging technologies reviewed in this manuscript, including advanced recirculating systems, biofloc technology, anammox and comammox nitrogen removal, nanotechnology applications, advanced oxidation processes (AOPs), bioencapsulated oral vaccines, integrated multi-trophic production, biochar-based nutrient recycling, and genetic improvement, collectively offer a pathway toward sustainable intensification that can meet growing seafood demand while reducing environmental footprint. Individual technologies present distinct strengths and limitations that determine their applicability across production contexts. Recirculating systems provide unparalleled water efficiency and environmental control but require substantial capital and technical capacity. Biofloc technology offers lower-cost water quality management with immunostimulation benefits but demands careful operational oversight. Anammox and comammox processes reduce energy and carbon requirements for nitrogen removal by 30-50% but require extended start-up periods and stable operating conditions . Nanotechnology enables targeted interventions but faces regulatory and safety uncertainties. Advanced oxidation processes effectively degrade recalcitrant pollutants but carry energy costs of 0.5-2.0 kWh/m^3 and potential byproduct formation . Oral vaccination through bioencapsulation promises non-invasive disease prevention but requires further development for commercial scalability. Integrated multi-trophic models transform waste into resources but increase system complexity. Biochar provides low-cost adsorption and carbon sequestration but requires regeneration or replacement, and its production necessitates pyrolysis infrastructure . The optimal implementation pathway increasingly involves hybrid configurations that combine complementary technologies. Integration of automation and AI with recirculating systems enables precision management that optimizes performance while reducing labor demands. Combining biofloc with ultrafiltration or anammox achieves nutrient removal and pathogen elimination that neither technology accomplishes alone. Coupling electrochemical AOPs with biochar filtration achieves sequential degradation and adsorption with synergistic energy savings . Coupling genetic improvement with biomarker development accelerates selection progress and enables non-invasive health assessment. These synergies suggest that the greatest advances will come not from any single technology but from thoughtful integration across disciplinary boundaries. Realizing this potential requires parallel progress in technology development, capacity building, and policy reform. Research must address remaining technical barriers, including cost reduction, scalability, and context-specific adaptation. Training and extension programs must equip producers and technicians with the skills required for advanced system management. Regulatory frameworks must evolve to accommodate novel technologies while safeguarding environmental and public health. With coordinated effort across these fronts, the emerging approaches reviewed here can transform aquaculture into a model of sustainable food production that contributes to food security, economic development, and environmental resilience.

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