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Water Environment Optimization and Animal Health Evaluation Under Sustainable Marine Aquaculture Systems

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Abstract Sustainable marine aquaculture requires effective management of water quality while maintaining animal health and production efficiency. In intensive and high-density farming systems, the accumulation of organic matter, nutrients, and toxic nitrogenous compounds, together with fluctuations in temperature, dissolved oxygen, pH, and salinity, can destabilize the aquatic environment and increase physiological stress and disease susceptibility in cultured animals. This review summarizes recent approaches to water environment optimization and animal health evaluation within sustainable marine aquaculture systems. Particular attention is given to the dynamic interactions among physicochemical conditions, nutrient cycling, sediment-water processes, microbial communities, and animal physiological responses. Conventional approaches, including aeration, water exchange, biological filtration, probiotics, and ecological regulation, are discussed together with advanced systems such as recirculating aquaculture systems, biofloc technology, integrated multi-trophic aquaculture, and resource-recovery approaches. The effects of environmental stress on animal metabolism, oxidative balance, immune responses, tissue integrity, growth, and disease susceptibility are also examined. In addition to conventional growth and survival indicators, biochemical, immunological, histological, molecular, and microbiome-based biomarkers provide complementary approaches for evaluating animal health and identifying early responses to environmental stress. An integrated framework linking water-quality monitoring, microbial regulation, animal health assessment, and precision management is proposed. A case study framework is further presented to evaluate environmental conditions, animal physiological status, and production performance throughout the culture cycle. Future development of sustainable marine aquaculture will increasingly depend on real-time sensing, Internet of Things technologies, multi-omics analysis, and artificial intelligence for dynamic risk assessment and adaptive management. Integrating water environment optimization with animal health evaluation may provide a more comprehensive basis for improving environmental sustainability, production stability, and animal welfare in marine aquaculture systems.

Keywords Sustainable marine aquaculture; Water environment optimization; Animal health; Microbial community; Precision aquaculture

1 Introduction

Marine aquaculture has become a central component of the global seafood supply because aquaculture now provides a large share of fish for human consumption and has, on average, overtaken capture fisheries as the main seafood source. At the same time, its rapid expansion has intensified debate over how to reconcile production growth with environmental protection, especially in coastal and offshore systems where nutrient release, habitat pressure, and climate-related disturbances can undermine long-term sustainability (Naylor et al., 2021). The challenge is therefore no longer whether marine aquaculture should grow, but how it can grow within ecological limits while remaining economically viable and socially acceptable. Reviews of sustainable aquaculture consistently argue that future progress depends on reducing localized pollution, improving resource-use efficiency, strengthening transparency and governance, and adapting farming practices to changing physical and biological conditions in the production environment.

The sustainability challenge is particularly acute in marine farming because production benefits are coupled to a water environment that is both the culture medium and the receiving environment for wastes. Expansion in marine finfish and coastal farming has been associated with concerns over eutrophication, habitat degradation, disease

outbreaks, chemical use, and competition for marine space, even though improved management has reduced some farm-scale impacts under modern operating conditions. This tension explains why sustainable marine aquaculture is increasingly framed not as simple output maximization, but as a problem of environmental fit, carrying capacity, and spatial planning. Site selection in areas with suitable depth, flushing, and ecological resilience is repeatedly identified as a primary preventive strategy, because well-sited farms and appropriate management can minimize water-column and benthic impacts before they become chronic constraints on production or public acceptance (Cerbule et al., 2021).

Within this framework, water environment quality is a direct determinant of animal performance, health, and system stability. Water quality is one of the prime factors governing aquaculture success, and even slight shifts in key variables such as temperature, pH, and dissolved oxygen can induce physiological and behavioral stress, reduce growth and reproduction, and increase susceptibility to disease (Marx and Sundaray, 2020). The biological dimension of the water environment is equally important. Microorganisms regulate nutrient cycling and water-quality maintenance, but unstable microbial assemblages are closely associated with disease occurrence in aquaculture, and shrimp physiological status has been shown to track variation in both gut and ambient microbiota. This means that animal health in marine culture systems reflects not only chemistry and physics, but also the ecological structure of the surrounding microbial environment.

Sustainable water-environment management therefore aims to optimize culture conditions for animals while simultaneously limiting waste accumulation, off-site pollution, and ecological risk. In practical terms, this requires continuous assessment of physical, chemical, and biological indicators, combined with management strategies that reduce nutrient losses, improve recycling, and maintain system function under variable seasonal and climatic conditions. Future-oriented frameworks extend this objective beyond monitoring alone. They emphasize integrated treatment technologies, water reuse, circular nutrient management, and governance systems that match technological options to local environmental capacity and regulatory context, so that productivity gains do not come at the expense of ecosystem health. Against this background, the present paper examines how water environment optimization and animal health evaluation can be combined within sustainable marine aquaculture systems, with the goal of clarifying the links among environmental control, biological response, and long-term production sustainability.

2 Water Environmental Dynamics in Marine Aquaculture Systems

2.1 Physical and physicochemical environmental factors

Physical and physicochemical factors set the immediate environmental template within which marine aquaculture organisms grow, feed, and respond to stress. In farm waters, temperature, salinity, dissolved oxygen, and pH are repeatedly identified as core variables because they govern both basic habitat suitability and short-term fluctuations in culture conditions, while broader reviews show that changes in these parameters alter physiology, metabolism, and behavior in ways that directly affect welfare and productivity (Zhang et al., 2020). In practical monitoring frameworks, these variables are treated as the principal physical indicators of water quality status, and their sensitivity to seasonality, rainfall, and farm management makes them especially important for sustainable marine production.

Their dynamics are not controlled by temperature alone, but by interacting atmospheric, hydrodynamic, and biological processes that can produce substantial short- and long-term variation across sites and even among cages. Longitudinal observations at salmon farms showed repeated hypoxic episodes below recommended optimal concentrations and strong spatial heterogeneity in dissolved oxygen, while regression analyses identified temperature, wind speed, and phytoplankton-related optical signals as important predictors of oxygen variability. Seasonal field studies in Mediterranean cage-farming areas similarly found significantly lower dissolved oxygen near cages during summer, indicating that local farm metabolism and seasonal stratification can depress oxygen availability even where the overall water body retains general seawater characteristics (Kucuksezgin et al., 2021).

2.2 Nutrient and organic matter dynamics

Nutrient and organic matter dynamics in marine aquaculture are driven primarily by external feed loading, animal excretion, and incomplete retention of nitrogen and phosphorus within harvested biomass. A substantial fraction of feed-derived nutrients is not assimilated by cultured animals, which elevates nitrogen and phosphorus concentrations in farming areas and makes nutrient enrichment a central mechanism of water-quality deterioration. Modeling and field studies further show that nutrient-use efficiency is often limited, with large shares of nitrogen and phosphorus partitioned to sediments or lost from farms, reinforcing the need to interpret pond, cage, and coastal systems as active biogeochemical reactors rather than simple holding environments (Zhang et al., 2020).

Once introduced, these nutrients do not remain static, but cycle through water, microbes, phytoplankton, and sediments in ways that reshape trophic structure and organic matter processing. In estuarine shrimp ponds, dissolved inorganic nutrient concentrations changed distinctly over growth stages and sediment porewaters contained much higher nutrient concentrations than the overlying water, indicating strong regeneration and upward supply from sediments. Experimental work on feed-detritus balance likewise showed that excessive nutrient release from feed and sediments stimulates algal proliferation, whereas a more balanced carbon:nitrogen:phosphorus regime supports a healthier microbial loop and more complete nutrient utilization, linking nutrient stoichiometry to both water quality and biological stability (Cao et al., 2024).

2.3 Sediment-water interactions and environmental deterioration

Sediment-water interactions are a critical pathway through which marine aquaculture converts pelagic waste loading into longer-term environmental deterioration. Excess feed, feces, and biodeposits accumulate on the bottom, where they enrich sediment organic matter, stimulate benthic respiration, and promote hypoxia and eutrophication in coastal waters (Kim et al., 2021). These effects are not limited to finfish farms: shellfish systems can also concentrate particulate organic matter in sediments through biodeposition, and infrastructure such as cages and long lines can modify local hydrodynamics in ways that increase deposition around farms.

As deterioration progresses, sediments become active sources of reduced compounds and regenerated nutrients that feed back on the overlying water column and benthic biota. Field and experimental studies show that aquaculture-driven organic enrichment compresses oxic and suboxic zones, accelerates oxygen and nitrate depletion, and shifts mineralization toward sulfate reduction and sulfide accumulation, while strongly impacted sites exhibit biodiversity loss and opportunistic benthic assemblages beneath or close to cages (Han et al., 2026). In semi-enclosed and lagoon systems, these sediment feedbacks can be especially severe because anoxia, high ammonium, and phosphorus remobilization intensify under weak flushing, making hydrodynamism and carrying-capacity control central to preventing persistent degradation. The redox compression and sulfide buildup associated with increasing organic loading are shown clearly in sediment quality profiles used to classify benthic enrichment effects.

3 Water Environment Optimization Technologies

3.1 Aeration, water exchange and hydrodynamic regulation

Aeration and water exchange remain the most direct technologies for correcting oxygen limitation and maintaining acceptable culture conditions in intensive aquaculture. Artificial aeration is essential under high stocking density because sustained dissolved oxygen supply underpins animal survival and system performance, while recent work also shows that aeration efficiency depends not only on equipment type but on seasonal conditions, suspended solids, dissolved solids, and aerator placement within the culture unit (Ramesh et al., 2024). In practical terms, water-environment optimization therefore requires matching aerator configuration to pond or tank hydraulics rather than treating oxygen input as an isolated intervention. Hydrodynamic regulation is equally important because flow structure determines mixing, solids transport, and the spatial uniformity of water quality. Experimental work on in-pond raceway systems showed that plug-flow aeration devices can create self-circulating flow fields, improve water exchange, and enhance dissolved oxygen retention through secondary flows, while recent hydrodynamic analyses of recirculating systems emphasize that uniform horizontal flow helps concentrate

residual feed and feces for removal and is therefore central to tank self-cleaning design. Together, these findings indicate that oxygen control and solids control should be designed as a coupled hydraulic problem.

Beyond basic aeration, optimization increasingly depends on predicting oxygen dynamics and aligning hydraulic energy with animal and system needs. A 96-day aeration study achieved 97% accuracy in forecasting dissolved oxygen with a seasonal SARIMA model, suggesting that proactive oxygen management is feasible when seasonal variability is explicitly incorporated, while industrial RAS reviews note that inlet-driven hydrodynamics, tank geometry, hydraulic retention time, and drive-equipment placement jointly determine flow pattern distribution and growth conditions (Ramesh et al., 2024). This supports a shift from reactive water-quality correction toward predictive flow-field management. Water exchange itself must also be used strategically, because poorly regulated renewal can increase water use without solving internal waste accumulation. Intensive aquaculture studies report that conventional systems often face high ammonia, nitrogen accumulation, excessive water consumption, and recurrent disease, whereas improved raceway design has increased water exchange and dissolved oxygen simultaneously. For sustainable marine aquaculture, the goal is therefore not maximal exchange, but hydrodynamically efficient exchange that maintains oxygen, mobilizes wastes, and limits unnecessary water demand (Figure 1).

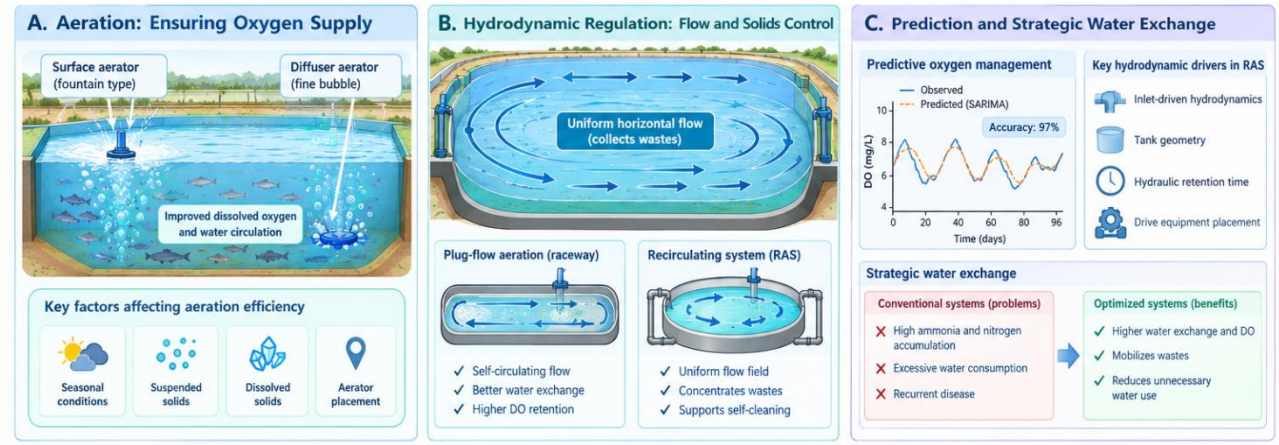


Figure 1 Integrated water environment management in intensive aquaculture

3.2 Biological and ecological approaches to water-quality management

Biological and ecological approaches seek to improve water quality by embedding purification functions into living components of the culture system. Reviews of aquaculture remediation show that microorganisms, macrophytes, aquatic animals, biofilters, and constructed wetlands are already widely used, and that ecological engineering is especially attractive because it can combine production and remediation with low risk of secondary pollution (Zhou et al., 2023). These approaches are particularly relevant for sustainable marine aquaculture because they reduce reliance on purely physical or chemical correction. Nature-based solutions offer one of the clearest ecological pathways for marine water optimization. Seagrass meadows can function as biological filters for inflowing aquaculture water by retaining suspended particles, fixing dissolved nutrients, regulating dissolved gases, and reducing exposure to pathogenic bacteria, making them suitable as pre-treatment ecosystems for flow-through pond or coastal farm systems. In marine settings where source water quality strongly shapes downstream culture performance, this kind of ecosystem service can reduce treatment demand before water enters the production unit.

Ecological engineering can also be designed as an internal farm-management strategy rather than only as an external buffer. Whole-process reviews conclude that ecological engineering is one of the best routes to green development in aquaculture and can improve animal welfare, stabilize water-treatment performance, and reduce environmental and public-health risks when system structure is properly managed. This broader framing is important because water-quality management in sustainable aquaculture depends on integrating species

composition, nutrient pathways, and farm layout into a single operational design. More targeted biological consortia can also achieve high pollutant removal from aquaculture wastewater. A pilot mussel-microalgae-bacteria ecosystem removed 94.67% of ammonia nitrogen, 92.89% of total phosphorus, and 77.78% of COD in batch treatment, while larger-scale field deployment maintained relatively low NH3-N, TN, TP, and COD concentrations over time (Geng et al., 2022). Such multi-trophic bioremediation systems are promising because they couple assimilation, filtration, and microbial processing within a biologically coherent treatment train.

3.3 Advanced treatment and resource-recovery technologies

Advanced treatment technologies increasingly aim not only to remove wastes but to recover value from them within a circular-economy framework. Recent reviews emphasize that the expansion of aquaculture has increased wastewater generation and therefore the need for advanced recycling methods, with candidate approaches including biofloc systems, aquaponic-aquaculture, microalgae culture, algal-bacterial systems, membrane bioreactors, moving-bed bioreactors, and electrochemical methods (Huang et al., 2024). The technological direction is therefore shifting from end-of-pipe disposal toward integrated recovery of nutrients, biomass, and treatment capacity. Recirculating aquaculture systems are central to this transition because they concentrate waste streams and allow treatment to be embedded within the production loop. In outdoor RAS, extractive organisms such as phototrophs and detritivores can convert a considerable share of wastes into biomass inside large treatment compartments, whereas indoor RAS typically rely on solid capture and nitrification as the main in-loop treatment steps. This distinction matters for marine aquaculture because system design determines whether wastes are primarily diluted, transformed, or biologically recaptured.

Microalgae-based integration is one of the most promising resource-recovery strategies because it links wastewater polishing with biomass generation. Recent synthesis shows that integrating microalgae into RAS can enhance nutrient recovery, improve environmental performance, and increase economic feasibility, while aquaculture effluent itself can serve as a nutrient source that lowers cultivation costs and supports greater system sustainability (Ende et al., 2024). Even so, effective implementation still depends on selecting tolerant strains and managing growth limitations imposed by wastewater composition. Resource recovery also requires treatment systems to be matched to farm-specific wastewater loads and downstream reuse pathways. Reviews of sustainable intensification conclude that side-stream treatment must be tailored to the daily discharge characteristics and location of each facility, while nutrient recycling into microalgal biomass is a particularly promising route for reducing waste and increasing productive output. At the same time, recent circular-treatment reviews indicate that improved nitrogen-removal pathways such as partial nitrification and anammox, together with attention to nitrous oxide emissions, are necessary if advanced treatment is to be both efficient and environmentally credible (Huang et al., 2024).

4 Environmental Stress and Animal Health Responses

4.1 Physiological and metabolic responses to water-quality stress

Water-quality stress first manifests as disruption of homeostasis, forcing cultured animals to reallocate energy from growth and routine physiological functions toward immediate survival. In crustaceans, suboptimal oxygen, temperature, salinity, pH, and ammonia conditions trigger compensatory metabolic responses that alter whole-body bioenergetics, while in fish dissolved oxygen is a particularly critical variable because hypoxia rapidly affects growth, welfare, and survival when levels remain severely depressed. This shift in energy allocation helps explain why environmental instability in culture systems often produces reduced performance even before overt pathology becomes visible. The specific metabolic phenotype depends on the stressor and exposure duration. Under acute low salinity, marine fish such as black seabream show rapid increases in reactive oxygen species and malondialdehyde, followed by signs of physiological adaptation and osmotic adjustment over time, whereas prolonged ammonia-N exposure in shrimp causes broader metabolic disturbances, reduced feed intake, and impaired overall health, indicating that acute compensation can give way to sustained dysfunction under chronic water-quality stress (Luo et al., 2024).

Water-quality stress also modifies behavior and tissue-level physiological processes in ways that can serve as early indicators of declining health. Reviews of fish responses show that variation in temperature, dissolved oxygen, salinity, pH, inorganic nitrogen, and pollutants affects physiology, metabolism, internal organs, and sensory function, with downstream effects on swimming, feeding, schooling, avoidance, and anxiety-like behavior (Zhang et al., 2020). These behavioral changes are not merely secondary signs, but part of the integrated stress response linking environmental quality to growth and welfare outcomes. At a broader systems level, intensification increases the frequency and severity of these responses because overcrowding, waste buildup, and water deterioration compound the metabolic cost of adaptation. Aquaculture reviews consistently report that intensive production exposes animals to interacting stressors that weaken growth, health, and immunity, while nutritional and physiological demands rise under stress as animals attempt to preserve performance under unstable environmental conditions.

4.2 Oxidative stress, immune responses and tissue damage

Oxidative stress is a central mechanism connecting water-quality deterioration to cellular injury in farmed aquatic animals. Environmental stressors such as hypoxia, salinity fluctuation, ammonia, nitrite, and pollutants promote reactive oxygen species overproduction and compromise antioxidant defenses, and this redox imbalance is now recognized as a major pathway through which deteriorating culture conditions impair growth, immunity, and survival. Because oxidative injury develops across multiple organs, it provides a unifying explanation for the broad pathological effects of poor water environments in both fish and crustaceans. The resulting damage is measurable at biochemical and histological levels. Under nitrogen and phosphorus stress, shrimp show elevated malondialdehyde together with gill and hepatopancreas injury, while ammonia-N stress in *Penaeus monodon* causes hepatopancreatic atrophy, deformation, and disruption of immune- and metabolism-related pathways, confirming that prolonged exposure converts biochemical stress into structural organ damage (Luo et al., 2024).

Oxidative stress also reshapes immune function rather than simply suppressing it uniformly. Hypoxia reduces immune competence and increases disease vulnerability in fish, but immune effects can be biphasic: chronic low oxygen in salmon elevated some basal innate immune markers while reducing antibacterial responsiveness after stimulation, indicating that stress may produce immune activation at rest yet impaired functional defense when a pathogen challenge occurs (Martyniuk et al., 2025). This nuance is important because apparent immune activation under stress does not necessarily indicate improved disease resistance. When oxidative and inflammatory pathways reinforce each other, tissue injury and systemic dysregulation intensify. Reviews of aquatic animals describe a ROS-inflammation cycle that drives organ dysfunction, immune suppression, and reduced stress resilience, while experimental heat stress in catfish confirms this pattern through lipid peroxidation, impaired immunity-related transcripts, and clear histoarchitectural lesions including barrier disruption, apoptosis, and inflammatory infiltration.

4.3 Environmental stress and disease susceptibility

Environmental stress increases disease susceptibility by weakening host defenses and shifting the host-pathogen balance toward infection. In aquaculture, chronic stress is associated with depressed immunity and greater pathogen susceptibility, and broad immunology reviews similarly conclude that acute and chronic environmental exposures can weaken the immune system and make aquatic animals more vulnerable to infection or coinfection (Martyniuk et al., 2025). This makes stress management a core disease-prevention strategy rather than only a welfare concern. The same principle holds under climate-linked environmental variability. Rising temperature, altered salinity, hypoxia, acidification, pollution, and nutrient stress can disrupt microbiomes, mucosal integrity, and inflammatory regulation, while reviews of marine fish and shellfish disease indicate that these combined stressors are likely to exacerbate disease risk as environmental conditions become more variable and extreme. Disease emergence in sustainable aquaculture must therefore be understood as an ecological consequence of environmental instability, not only as pathogen exposure.

Mechanistic studies in shrimp provide direct evidence that environmental stress can increase infection risk through microbiome disruption. Acute low-salinity stress increased *Vibrio parahaemolyticus* infection levels,

reduced gut microbial richness, and altered microbial functions in Pacific white shrimp, showing that sudden salinity drops can translate into greater pathogen success through dysbiosis-mediated loss of colonization resistance (Chang et al., 2024). These findings are especially relevant to coastal farming systems exposed to heavy rainfall and rapid salinity change. Environmental deterioration can also act on the pathogen side by enhancing virulence or creating conditions favorable for opportunists. Reviews of opportunistic bacterial disease show that climate change, eutrophication, pollution, and production intensification are contributing to a broader disease crisis, and work on *Aeromonas hydrophila* indicates that temperature, pH, ammonia, oxygen, and host condition jointly modulate bacterial pathogenicity and host susceptibility (Samsing and Barnes, 2024).

5 Animal Health Evaluation and Biomarker-Based Assessment

5.1 Conventional indicators of animal health

Conventional animal health evaluation in aquaculture still begins with easily observable production and performance outcomes, because growth, survival, and feed efficiency integrate the cumulative effects of environmental quality, nutrition, and disease pressure over time. Across fish and shrimp studies, higher growth is closely associated with better health status, while reduced survival and poorer feed conversion remain practical warning signs that culture conditions or biological resilience have deteriorated (Esmaeili, 2021; Khanjani, 2025). For this reason, routine farm-level assessment commonly uses survival rate, weight gain, specific growth rate, and feed conversion as first-line indicators of whether animals are maintaining acceptable health under a given production system. These conventional indicators are useful but incomplete, because animals can maintain growth under some treatments while showing meaningful differences in survival or physiological condition. In whiteleg shrimp post-larvae reared in recirculating systems, dietary treatments produced no significant growth differences but did alter survival and physiological status, while multi-factor environmental stress in *L. vannamei* reduced survival and daily growth and simultaneously disrupted serum and hepatopancreatic physiology (Barreto et al., 2026). This means that conventional performance metrics are necessary for health evaluation, but they are not sufficient to identify subclinical stress or early physiological deterioration.

Broader conventional assessment can also include simple vigor-related traits that reflect robustness under handling and environmental challenge. Comparative strain evaluation in Pacific white shrimp showed that dry-stress tolerance, jumping ability, transportation mortality, and net production performance can distinguish strain quality even when basic growth and survival do not differ significantly, highlighting the value of resilience-oriented field traits in applied health evaluation (Zhang et al., 2020). These indicators are especially relevant in sustainable marine aquaculture because animals are repeatedly exposed to salinity shifts, hypoxia episodes, and operational handling that are not captured by body weight alone. Evidence syntheses also support the use of production outcomes as population-level health readouts when assessing management interventions. A meta-analysis of probiotic use in penaeid shrimp found consistent improvements in survival, specific growth rate, and feed conversion ratio, showing that these conventional endpoints remain robust for judging whether a treatment meaningfully improves overall health and productivity at farm scale. In practice, conventional indicators therefore provide the baseline layer of health assessment, but they work best when interpreted alongside biomarkers that can reveal why performance is changing.

5.2 Physiological, biochemical and immune biomarkers

Physiological and biochemical biomarkers are used to detect stress responses before they become visible in production losses. In fish, hematological and blood biochemical variables such as red and white blood cells, hemoglobin, hematocrit, and total protein are widely used because changes in physiological status caused by pollution or nutritional stress are reflected in blood, although no single parameter is consistently sufficient across all contexts (Esmaeili, 2021). This has led to increasing emphasis on multi-parameter panels rather than reliance on one marker alone. In shrimp, immune and metabolic enzymes are central components of these panels because they reflect both nonspecific defense capacity and tissue condition. Established immunological tools identify hemocyte counts, phenoloxidase activity, radical oxygen intermediates, plasma antibacterial activity, and plasma protein concentration as useful markers of shrimp condition, while more recent experimental work continues to

use alkaline phosphatase, acid phosphatase, lysozyme, superoxide dismutase, catalase, ALT, AST, and malondialdehyde as key indicators of stress and immune status. Together, these markers link immune competence, oxidative balance, and organ function in a way that conventional growth indices cannot.

Their diagnostic value becomes clearer under defined environmental stress. Salinity challenge in black tiger shrimp significantly altered growth, survival, osmolality, free fatty acids, free amino acids, oxygen consumption, glucose, serotonin, hemocyte counts, and the expression of osmoregulatory and immune-related genes, showing that physiological biomarkers can resolve both acute adjustment and longer-term acclimation. Likewise, ammonia-N stress in *P. monodon* caused hepatopancreatic damage together with changes in oxidative stress, immune, metabolic, transcriptomic, and metabolomic markers, supporting the use of integrated biomarker suites for environmental risk assessment (Luo et al., 2024). Biomarker interpretation, however, requires caution because responses are often context dependent and can be diagnostically ambiguous when used in isolation. Reviews of fish welfare biomarkers emphasize that the same marker can reflect nutritional imbalance, environmental stress, disease, or antibiotic exposure, and therefore combinations of biomarkers with species-specific threshold values are needed to improve sensitivity and specificity. A summary figure usefully organizes the main nutritional, immune, oxidative, and physiological biomarkers currently applied in fish health assessment.

5.3 Molecular and microbiome-based health assessment

Molecular and microbiome-based assessment extends health evaluation beyond host phenotype to the host-microbe system that shapes resilience and disease emergence. Next-generation sequencing has clarified that microbiomes regulate metabolism, immune function, and resilience, and disease is increasingly understood through a holistic framework in which host condition, environment, and colonizing microorganisms interact rather than act independently (Mougin and Joyce, 2022). This shift is especially important in aquaculture because many disease outbreaks begin before obvious clinical signs appear. In shrimp, gut microbiota are tightly linked to survival, growth, and health status, yet their diagnostic use depends on understanding normal variation across life stage and farming context. Reviews show that environmental change, diet, age, disease, and habitat shifts all reshape shrimp gut microbiota, while earlier syntheses caution that abnormal disease-associated states cannot be identified reliably until normal microbiome structure has been characterized across species and culture systems (Holt et al., 2020). This makes contextual baseline data essential for any microbiome-based monitoring framework.

Recent studies show that microbiome profiles can support quantitative health prediction rather than only descriptive comparison. Across global whiteleg shrimp datasets, microbiome composition alone explained about half of the variation in larval survival and was predictive of key production outcomes, while longitudinal disease tracking showed that combining microbiota immaturity with disease-discriminatory taxa diagnosed shrimp health status with 91.5% accuracy and reflected disease severity (Shan et al., 2025). Molecular assessment is also moving from taxonomic signatures toward functionally informative diagnostics. During AHPND infection in P. monodon, biochemical testing combined with 16S rRNA analysis distinguished healthy and diseased shrimp and identified microbiome shifts associated with pathogen colonization, while a multi-disease meta-analysis found 18 common disease-discriminatory taxa that diagnosed shrimp health status with 90.0% accuracy across pathogens and life stages (Soo and Bhassu, 2022). Current evidence therefore supports molecular and microbiome-based tools as early-warning systems, especially when integrated with physiological and production indicators rather than used alone.

6 Coupling Water Environment Optimization with Sustainable Animal Health Management

6.1 Water quality-microbiome-animal interactions

Water environment optimization and animal health management are coupled most directly through the microbiome, because microbial communities simultaneously regulate nutrient cycling, water-quality maintenance, and host physiological stability (Sehnal et al., 2021). In aquaculture systems, unstable microbial environments are associated with disease occurrence, and broader reviews show that microbial diversity is closely linked to

productivity, animal performance, and the emergence of dysbiosis under environmental stress. This coupling is not restricted to the host gut, but spans water, sediment, and animal compartments that exchange microbes and metabolites across the production cycle. In shrimp ponds, intestinal physiology tracks variation in gut and ambient microbiota, while in fish and other aquatic vertebrates water chemistry, surrounding microbiota, diet, and anthropogenic disturbance all shape host-associated microbial structure with consequences for health and ecosystem function (Sehnal et al., 2021). The cross-compartment linkage between water, sediment, and intestine is especially clear in community-comparison plots of shrimp pond microbiota.

In practical farming conditions, water quality acts as a microbial filter that can stabilize or destabilize host-associated communities. Adequate water quality is described as essential to productivity and welfare, yet coastal and offshore farms experience more variable physicochemistry than land-based systems, which increases pressure on microbiome stability. Stressors common in aquaculture, including overcrowding, temperature change, chemotherapeutics, and handling, can increase pathogen abundance and disrupt the diversity and composition of skin and gut mucosal microbiota (Xavier et al., 2023). These observations support using dysbiosis itself as a management signal. Reviews of aquaculture microbiomes identify loss of beneficial microorganisms, expansion of harmful taxa, and loss of diversity as recognizable forms of dysbiosis, while increases in potential pathogens and shifts in community structure appear to be reliable indicators of microbial imbalance in farmed fish. Because microbiomes also respond rapidly to environmental disturbance and can be monitored with high-throughput, relatively low-cost sequencing or eDNA approaches, they are increasingly positioned as sensitive indicators for both host health and water-environment status (Sehnal et al., 2021).

6.2 Integrated monitoring and early-warning systems

Coupling water optimization with health management requires monitoring systems that integrate environmental, behavioral, and biological signals rather than tracking single variables in isolation. Conventional physicochemical sensing is valuable for continuous surveillance, but it remains limited for detecting unknown contaminant mixtures or additive biological effects, which is why biological early-warning systems were developed to complement routine water-quality measurements. In aquaculture specifically, fluctuations in dissolved oxygen, pH, temperature, light, and plankton density can increase disease vulnerability, and real-time sensor systems now allow farmers to detect deviations rapidly through connected devices (Bohara et al., 2023). Applied systems are moving toward integrated alert architectures that connect sensing, threshold logic, and real-time communication. IoT shrimp-pond monitoring platforms now track dissolved oxygen, pH, and temperature and can send automatic buzzer and smartphone alerts when values cross threshold levels. Comparable multi-sensory systems measure electrical conductivity, dissolved oxygen, pH, and temperature in real time and are designed to trigger early signals so corrective action can be taken immediately when water quality moves outside the safe range (Abdullah et al., 2021).

The strongest early-warning frameworks now fuse water quality with fish condition and disease indicators. In a commercial kingfish RAS, integrated monitoring linked controlled water chemistry, microbiota profiling, pathogen-specific digital PCR, and histological scoring into one framework for optimizing production quality and health surveillance. Disease-warning performance improves further when multiple data streams are fused, as shown by a nocardiosis warning system that combined water quality, body-surface features, and behavior and reached 94.08% integrated identification accuracy (Huang et al., 2024). A key implication is that monitoring should become dynamic, stage-specific, and fault tolerant. Recent IoT systems already incorporate growth-stage-based threshold models, anomaly alerts, and backup control features to reduce false alarms and improve reliability across pond scales. At the same time, rapid diagnostics based on sequencing, biosensors, CRISPR, drones, sensors, and AI are making disease detection faster and farm surveillance more actionable, although adoption still depends on training, cost, and operational fit (Bohara et al., 2023).

6.3 Precision management and adaptive aquaculture

Precision aquaculture provides the operational framework for converting monitoring data into adaptive

environmental control. Its core objective is to apply control-engineering principles so farmers can monitor, control, and document biological processes more effectively, replacing experience-based management with more knowledge-based and automated production systems. More recent syntheses place this shift within a broader sustainability agenda, arguing that blue transformation will require data-driven operations supported by predictive modeling, decision-support systems, and inclusive digital infrastructure. In practice, this means responding to spatial and temporal variability in pond and cage environments with real-time control. Precision aquaculture is explicitly defined around observing, measuring, and responding to space-time variability, and IoT-based systems now support real-time monitoring, control, and documentation of dissolved oxygen, pH, temperature, turbidity, salinity, ammonia, and other environmental variables. Because integrated sensor platforms can also include weather, water velocity, and ecosystem parameters, they support broader operational decisions than single-point water-quality logging alone (Yavuzcan and Mansour, 2026).

Adaptive control is becoming more autonomous and more tightly linked to production goals. Fuzzy-logic aquaculture systems now continuously monitor temperature, pH, dissolved oxygen, weather, and salinity and can automatically adjust aerators and pumps under changing conditions, achieving 98% model accuracy in one recent implementation (Nagothu et al., 2024). Reinforcement-learning control in RAS has extended this logic further by coupling feeding-rate optimization with water-quality management, producing 15.5% feed-conversion improvement, 96.8% water-quality maintenance, and 31.5% lower operating costs under dynamic condition. The next step is to make adaptive management explicitly health-responsive rather than environment-responsive alone. Behavior-based control systems already use stress feedback, growth modeling, and energy-cost optimization to regulate culture conditions, reducing stress-induced damage while improving profit relative to threshold-based control (Wang et al., 2025). Microbiota-manipulation approaches such as biofloc management point in the same direction, because they optimize water quality by steering microbial processes that convert waste into usable biomass while also supporting disease and health management. The main sensor and monitoring components commonly used in precision fish farming are summarized in a comparative technology table.

7 Case Study: Integrated Water Environment Optimization and Animal Health Evaluation in a Sustainable Marine Aquaculture System

7.1 Environmental monitoring and optimization during the culture cycle

A representative sustainable marine aquaculture case begins with high-frequency tracking of the main physicochemical drivers across the culture cycle, because water quality remains a principal limiting factor and changes with season, farming activity, and enclosure type. In practical monitoring programs, core indicators include temperature, pH, salinity, dissolved oxygen, nutrients, and related pollution signals, and recent IoT platforms now allow these variables to be measured continuously with real-time dashboards, alerts, and historical records that support timely intervention during critical periods (Zhang et al., 2020). During the production cycle, optimization is most effective when monitoring captures both temporal instability and within-farm spatial heterogeneity. Real-time cage-scale sensing in salmon farming showed that dissolved oxygen varied strongly among cages and was shaped by tidal advection and cage position, with downstream cages experiencing lower oxygen, while a 56-day shrimp pond study found that dissolved oxygen and pH became more unstable in mid-to-late culture and that ammonia and nitrite spikes signaled organic accumulation and microbial imbalance. These results support adaptive actions such as adjusting aeration, feed input, water exchange, and biomass distribution according to culture stage and local hydrodynamics rather than applying uniform farm-wide control.

A stronger case-study design also includes automated and wireless sensing because manual sampling often misses rapid deviations in critical parameters. Reviews of aquaculture sensor systems show that instability in pH, temperature, and dissolved oxygen during production can raise mortality risk and delay management response when monitoring is not automated, whereas wireless multi-sensor systems can integrate temperature, pH, dissolved oxygen, conductivity, and derived salinity for continuous in situ surveillance (Lin et al., 2021). This is particularly useful in marine or brackish farms where salinity shifts and oxygen decline interact with feeding intensity and weather variability over short time scales. Optimization becomes more proactive when prediction is

coupled to monitoring. IoT-machine-learning systems have been used to identify thousands of anomalies in dissolved oxygen and turbidity and to trigger automated corrective actions such as oxygenation and pH adjustment, while systematic review evidence indicates that real-time sensing is already improving growth and reducing mortality in systems such as biofloc and RAS (Figure 2) (Baena-Navarro et al., 2025). In an applied case-study framework, this means the culture cycle is no longer managed only by periodic observation, but by continuous detection, prediction, and intervention calibrated to evolving environmental risk.

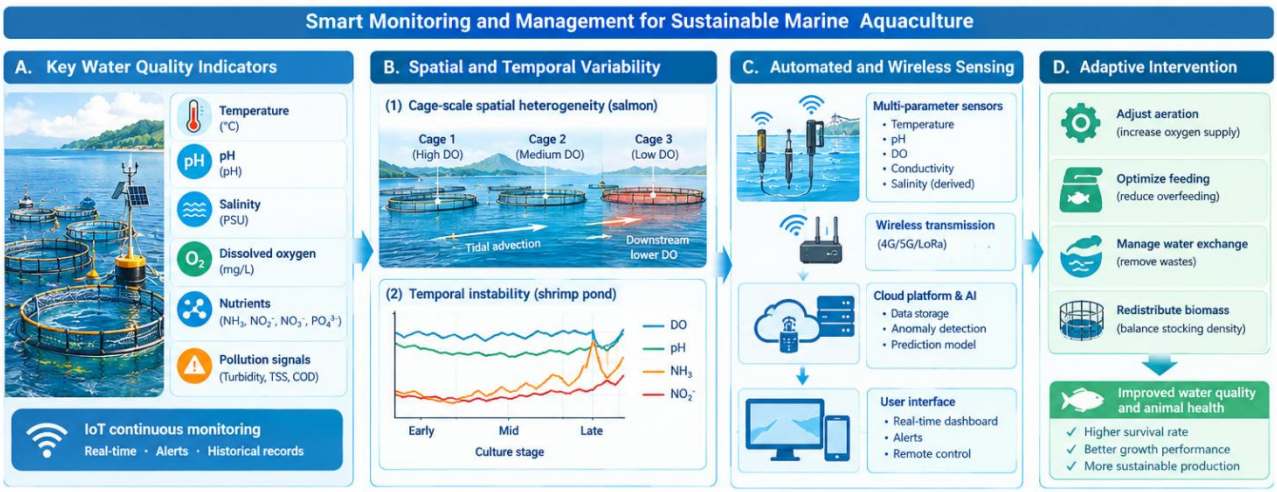


Figure 2 Framework for smart monitoring-based water environment management in sustainable marine aquaculture

7.2 Evaluation of animal growth, physiology and health status

Animal evaluation in an integrated case study should combine conventional production indices with mechanistic health indicators. Growth rate, feed conversion, survival, gill condition, lesion frequency, and behavioral stress responses provide a practical welfare profile at farm scale, while broader biomarker frameworks show that nutritional, physiological, immune, oxidative, and pathological status can be detected earlier through targeted biochemical and omics-based measurements (Muninathan et al., 2025). This layered approach is important because production metrics alone often identify decline only after subclinical stress has already affected animal performance. A realistic marine case also needs to track how environmental pressure is expressed biologically over time. In shrimp cultured under different stocking densities in a biofloc system, increasing density reduced final weight, survival, and feed efficiency while depressing lysozyme, phenoloxidase, and antioxidant enzyme activities, showing that routine performance losses were accompanied by measurable immune and oxidative impairment (Khanjani, 2025). Likewise, stress-response synthesis in crustaceans indicates that water deterioration, crowding, and waste accumulation alter appetite, intestinal condition, energy allocation, and molecular pathways, supporting the use of integrated physiological assessment rather than single-point health checks.

Nutritional and microbial interventions can also be incorporated into case-study health evaluation because they reveal whether the system is supporting resilience rather than merely avoiding mortality. In juvenile L. *vannamei*, guanidinoacetic acid supplementation increased weight gain and specific growth rate, lowered feed conversion ratio, and improved antioxidant and nonspecific immune indices, while probiotic supplementation enhanced shrimp growth, survival, and immune-gene expression and improved resistance to Vibrio challenge (Lin et al., 2021). These responses are useful in integrated case analysis because they connect environmental management with host capacity to maintain growth and defense under operational stress. Health evaluation should also remain sensitive to diet-related trade-offs and short-term versus longer-term outcomes. Replacement of fish meal with fish protein hydrolysate improved some early immune responses and short-term *Vibrio* resistance, but higher substitution levels reduced growth and midgut structural quality, showing that apparent immune benefits do not always translate into better overall performance. For case-study interpretation, this means animal health should be judged from converging evidence across growth, tissue condition, antioxidant balance, and disease resistance rather than from any single favorable biomarker.

7.3 Integrated assessment of environmental and animal health outcomes

The final step in an integrated case study is to evaluate whether environmental optimization and animal-health responses improve together. Evidence from combined habitat and water-quality assessment shows that dissolved oxygen variability, sediment organic loading, and nutrient accumulation are major drivers of welfare decline and production inefficiency, whereas interventions such as sediment removal, shoreline vegetation adjustment, and feeding optimization improve oxygen processes, nutrient status, growth, health, and survival (Muninathan et al., 2025). This supports using a joint assessment framework in which environmental and biological endpoints are interpreted as parts of the same system rather than separate monitoring streams. Integrated farming models further show that environmental recovery can coincide with improved production performance. In a marine pond ecosystem model, integrated aquaculture maintained a healthier environment and balanced ecosystem while increasing profit, and at optimized carrying capacity nitrogen and phosphorus removal rose by 51.48% and 55.55%, respectively, alongside a 51.59% profit increase. A land-based IMTA case similarly showed that adding mussels and macroalgae substantially reduced ammonia, nitrate, and nitrite while supporting strong finfish growth, indicating that nutrient-removal functions can be embedded directly into production design.

Integrated assessment should also include microbial quality because water optimization without microbial surveillance can miss disease-related deterioration. Multiparametric microbial monitoring in a *Mediterranean mariculture* system showed that microbial loads increased markedly in summer and that the combined inventory of abundance, diversity, and metabolism provided a useful indicator of farming-water quality, supporting seasonal disease-risk surveillance. This is especially important in sustainable marine systems where favorable physicochemical values may still coexist with elevated pathogen pressure or microbiome instability. A robust case-study conclusion therefore combines environmental metrics, microbial signals, animal biomarkers, and production outcomes into one decision framework. Reviews of integrated sustainability assessment show that feed composition (Muninathan et al., 2025), feed conversion, animal health, and environmental performance are linked but do not always improve in parallel, so trade-offs must be evaluated explicitly rather than assumed away. In practice, the most credible sustainable marine aquaculture systems are those in which continuous water monitoring, biologically informed health evaluation, and integrated nutrient-management design converge to deliver stable water quality, resilient animals, and lower environmental discharge.

8 Sustainability, Challenges and Future Perspectives

Optimized aquaculture systems can improve environmental and economic performance simultaneously rather than forcing a fixed trade-off between them. Comparative global analysis across 57 aquaculture systems found that the three pillars of sustainability are, on average, complementary, and that a sustainable aquaculture industry is achievable with appropriate policy and investment choices. At the production-system level, integrated marine pond aquaculture increased profit by 51.59% while also increasing nitrogen and phosphorus removal by 51.48% and 55.55%, respectively, showing that ecological optimization can directly strengthen farm economics. Environmental benefits are especially clear when optimized systems reduce wastes, improve nutrient recovery, and lower dependence on open discharge. Sustainable marine finfish aquaculture reviews identify recycling or remediation of fish-production wastes as central to affordability and sustainability, while recirculating aquaculture systems, integrated multi-trophic aquaculture, and improved disease-resistance strategies are reported to substantially reduce water use, nutrient discharge, and environmental impact Precision aquaculture adds an economic layer to these gains by improving resource-use efficiency and waste management, while also protecting investments and improving business stability through better risk assessment.

Well-sited and efficiently operated marine systems can also reduce local ecological pressure while maintaining productivity. Offshore aquaculture has become more environmentally sustainable through improved siting that preserves benthic communities and water quality, and properly sized, efficiently operated offshore farms can have negligible environmental impact. In parallel, field and review evidence on IMTA indicates opportunities for lower environmental impact, higher productivity, and increased profitability compared with conventional monoculture, especially when complementary trophic functions are intentionally designed into the system. Some optimized

systems also generate broader ecosystem-service value beyond the farm gate. Stakeholder analysis in mariculture found support for shellfish aquaculture as a contributor to improved water quality, and nutrient removal by mariculture in EU coastal waters alone has been valued at US$20-30 billion per year. Consistent with this, brackishwater IMTA outperformed conventional polyculture by improving inorganic nutrient conditions in pond water, reinforcing the case that water-environment optimization can create both farm-level and societal returns.

The main limitation is not the absence of sustainable technologies, but uneven adoption caused by cost, regulation, and context-specific feasibility. Recent synthesis shows that recirculating systems, IMTA, and selective health technologies can substantially mitigate impacts, yet uptake remains constrained by high capital costs, regulatory barriers, and limited accessibility for small-scale producers. Precision aquaculture faces the same pattern: high initial investment, infrastructure limitations, technical complexity, data-management burdens, and training needs continue to limit implementation despite clear operational promise. Knowledge gaps also remain substantial in wastewater governance and pollution characterization. Global review evidence indicates that spatial heterogeneity in aquaculture pollutants is still insufficiently understood, and that the lack of an integrative framework linking tailored technologies with regional governance continues to hinder transition toward green and low-carbon aquaculture. This gap is mirrored in mariculture management, where stakeholders identified the need for better understanding of spatial and temporal land-use variation across catchments in order to manage water quality effectively.

Several widely promoted systems also have unresolved performance uncertainty. Recent IMTA review evidence concludes that practical delivery of its environmental promise remains unclear, because many assessed systems are theoretical or non-optimized and because life-cycle and cost-benefit studies often reach different conclusions. RAS faces a parallel challenge: more than 80% of companies surveyed showed inadequate financial performance with payback periods averaging over 8 years, and the sector still needs more reliable commercial-scale data and better operational understanding for standardization. Animal-health management remains another persistent bottleneck. Disease control still relies heavily on vaccines, antibiotics, chemicals, and functional feeds, but vaccine availability is limited for many species and regions, while overuse of antibiotics and chemical treatments drives resistance problems in both bacterial pathogens and parasites. More broadly, sustainable marine aquaculture still faces unresolved pressures from eutrophication, habitat impacts, feed dependency, exotic species risks, and inadequate medication practices, indicating that technical optimization alone is not sufficient.

Future progress appears most likely to come from precision sustainability frameworks that couple technological innovation with adaptive management and inclusive governance. One recent review explicitly proposes such a framework, integrating technology, adaptive management, and governance to align aquaculture development with environmental protection and social equity. Earlier precision-farming work points in the same direction, arguing that aquaculture must move from experience-driven to knowledge-driven production and that emerging technologies and automated systems will be central to that shift. Digital technologies are likely to shape the next phase of water-environment optimization and health management. Integrated IoT, AI, and blockchain frameworks are reported to support real-time monitoring, precision feeding, disease detection, traceability, predictive analytics, and automation, while future innovation is expected to focus on adaptive machine learning, edge computing, and scalable data-driven control. Related precision-aquaculture syntheses also point to blockchain, digital twins, multimodal sensor fusion, autonomous robotics, and explainable AI as likely next-generation tools for transparent and automated sustainable production.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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