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Water Quality Control and Fish Health Management in Recirculating Aquaculture Systems

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International Journal of Marine Science, 2026, Vol.16, No.4 doi: 10.5376/ijms.2026.16.0017

Received: 13 Jun., 2026

Accepted: 18 Jul., 2026

Published: 30 Jul., 2026

Preferred citation for this article:

Zhao F., and Li X.M., 2026, Water quality control and fish health management in recirculating aquaculture systems, International Journal of Marine Science, 16(4): 217-230 (doi: 10.5376/ijms.2026.16.0017)

Abstract Recirculating aquaculture systems (RAS) have emerged as an important technology for sustainable aquaculture development due to their advantages in water conservation, environmental control, and high-density fish production. However, maintaining optimal water quality and preventing fish health problems remain major challenges in intensive RAS operations. This review focuses on the relationship between water quality control and fish health management in recirculating aquaculture systems. The fundamental mechanisms regulating water quality are first discussed, including the dynamics of dissolved oxygen, temperature, pH, ammonia, nitrite, nitrate, carbon dioxide, and microbial communities. The impacts of water quality fluctuations on fish physiological responses, growth performance, immune function, and disease susceptibility are further analyzed. Subsequently, advances in monitoring technologies, including sensor networks, Internet of Things (IoT) platforms, and data-driven approaches, are summarized for real-time environmental assessment and management. Strategies for maintaining stable water conditions, such as mechanical filtration, biological treatment, oxygen regulation, nutrient management, and microbial regulation, are evaluated. A case study framework is presented to demonstrate the integration of water quality monitoring, fish health assessment, and intelligent management strategies in commercial RAS facilities. Furthermore, the potential applications of artificial intelligence, predictive modeling, and automated control systems are discussed. Future research should focus on multi-source data integration, intelligent decision-support systems, and sustainable management technologies to improve production efficiency, fish welfare, and environmental sustainability in recirculating aquaculture.

Keywords Recirculating aquaculture systems; Water quality control; Fish health management; Intelligent aquaculture; Biofiltration technology

1 Introduction

Recirculating aquaculture systems (RAS) have emerged as a major technological pathway for intensifying aquaculture while reducing its dependence on large volumes of water and limiting effluent release. Their development has accelerated because RAS can operate in controlled indoor environments, recycle most of the culture water, improve biosecurity, and support more predictable production under environmental and climate-related constraints (Gupta et al., 2024). Earlier and more recent reviews alike describe RAS as high-control, high-reuse production systems whose core value lies in decoupling fish farming from local water availability while improving waste management and nutrient recycling. At the same time, the importance of RAS is not only environmental but strategic: these systems are increasingly viewed as a means to expand aquaculture production with lower ecological impact, stronger containment of escapees and pathogens, and greater resilience to drought, salinity shifts, and other external stressors that threaten open systems (Ahmed and Turchini, 2021). This combination of production control and environmental performance has made RAS central to discussions of sustainable aquaculture, even though energy demand, capital cost, and managerial complexity still constrain broader adoption.

The advantages of RAS, however, depend on maintaining water quality within narrow and species-specific limits, because fish in intensive recirculating environments are continuously exposed to the same water matrix and to the consequences of any treatment failure. Water quality in RAS includes physical, chemical, and biological dimensions, and the key variables routinely monitored include temperature, dissolved oxygen, pH, salinity, oxidation-reduction potential, turbidity, and suspended solids, all of which shape fish growth, stress, and disease risk (Dai et al., 2025).

Pollutants generated by feed inputs and fish excretion, particularly particulate matter, ammonia, nitrite, nitrate, carbon dioxide, and microbial loads, can accumulate in recirculating loops and impair both system performance and animal health if removal processes are insufficient (Li et al., 2023). Reviews focused on fish welfare in RAS further emphasize that degraded water quality affects not only survival and feed conversion but also gill integrity, immune responses, and behavior, making water quality a direct determinant of fish health rather than a background husbandry variable (Holan et al., 2020; Bjørgen et al., 2024). This relationship is especially important in high-density production, where organic loading, bacterial growth, and fluctuating oxygen conditions can propagate rapidly through the system and magnify subclinical stress into health and welfare problems (Lindholm-Lehto, 2023).

Research in recent years has therefore shifted from describing individual water quality variables toward integrated water quality-based fish health management. Current work highlights the need for rapid, real-time, and automated monitoring technologies, including IoT-linked sensors, online measurement platforms, and behavior-based surveillance tools that can detect emerging deterioration before overt disease or mortality occurs (Lindholm-Lehto, 2023). This shift is reinforced by disease-management studies showing that effective fish health protection depends on preventive surveillance, quality health data, and early warning rather than treatment after outbreaks, especially because conventional chemotherapy can disrupt biofilters and destabilize water quality in RAS (Holan et al., 2020). Parallel advances in predictive analytics have extended this approach by using machine learning and knowledge-based systems to identify water quality degradation, diagnose disease risks, and support decision-making before losses become severe (Islam et al., 2024). Together, these developments show that fish health management in RAS is increasingly becoming a data-centric discipline in which water quality control, system monitoring, and biosecurity are operationally inseparable (Gupta et al., 2024).

Against this background, the objective of water quality-based fish health management is no longer simply to keep individual parameters within acceptable ranges, but to build integrated control frameworks that connect environmental monitoring, treatment performance, fish responses, and management decisions. Recent reviews argue that full control of water quality and optimization of rearing conditions are the main conditions for sustainable RAS operation, while also noting that the field still lacks standardization in what parameters are measured, how often they are measured, and what fluctuations are acceptable across systems and species (Gupta et al., 2024). Important methodological gaps also remain, including incomplete reporting of water quality in fish health studies, inconsistent interpretation of health indicators such as gill responses, and the need for commercial-scale data that can support more reliable and transferable management models (Bjørgen et al., 2024). Accordingly, this paper is grounded in the premise that intelligent water quality control must combine conventional engineering with biological surveillance and predictive modeling to support fish welfare, stable production, and lower environmental cost (Kamali et al., 2022). In that sense, the central research task is to clarify how water quality information can be translated into actionable fish health management strategies for next-generation RAS.

2 Fundamental Mechanisms of Water Quality Regulation in Recirculating Aquaculture Systems

2.1 Dynamics and control of major water quality parameters

Water quality regulation in RAS depends on controlling a tightly coupled set of variables, especially ammonia, nitrite, nitrate, dissolved oxygen, and pH, because these parameters shift continuously with feeding, fish metabolism, biofilter activity, and water exchange (Lindholm-Lehto, 2023). Dynamic modeling shows that parameter stability is not static but emerges from feedback loops linking waste production, oxygen demand, and treatment-unit performance, which is why operational changes in stocking density, feed intensity, or aeration can rapidly alter system water chemistry (Udayakumar et al., 2025).

Among the major parameters, dissolved oxygen, temperature, and pH have especially strong control effects because they influence both fish physiology and the toxicity or transformation of nitrogenous wastes. In RAS, increasing temperature lowers dissolved oxygen availability and increases ammonia toxicity, while extreme pH directly destabilizes other critical parameters; field observations likewise show that pH variability reflects the combined effects of nitrification, carbon dioxide stripping, and buffering, making precise pH control essential for stable operation (Pepe-Victoriano et al., 2025).

2.2 Biological processes maintaining water quality in ras

The core biological mechanism maintaining water quality in RAS is microbial nitrogen conversion within biofilters, where toxic ammonium is oxidized into nitrite and then nitrate, reducing acute toxicity in the culture water (Lindholm-Lehto et al., 2020). This process is now understood as more complex than the classical two-step nitrification model, because coupled nitrogen removal can also involve aerobic denitrifiers, anammox organisms, and comammox microorganisms that together improve total nitrogen removal under low-water-exchange conditions (Preena et al., 2021).

Biological regulation also depends on community structure and engineered enhancement of microbial function rather than on nitrification alone. In recirculating pond systems, bacteria-microalgae associations with biofilm carriers reduced total nitrogen, TAN, and nitrite while increasing functional genes linked to ammonia oxidation and denitrification, and biofloc biofilters similarly concentrated denitrifiers, nitrifiers, and phosphorus-removing microorganisms in the reaction zones where most nutrient removal occurred.

2.3 Effects of water quality fluctuations on fish physiological responses

Water quality fluctuations affect fish first through stress physiology, and dissolved oxygen depletion is one of the most immediate threats in intensive systems. Hypoxia below about 1-2 mg/L for even a few hours can suppress growth and cause mortality, while broader reviews of RAS species responses show that excessively low dissolved oxygen disrupts system balance and produces losses that can quickly become unacceptable under intensive culture conditions (Dai et al., 2025).

Nitrogenous waste accumulation produces a second major physiological pathway of harm because elevated ammonia alters biochemical, physiological, immunological, and homeostatic processes, increasing disease susceptibility. This toxicity is not fixed, since its severity rises or falls with pH, temperature, salinity, dissolved oxygen, species, and life stage, and RAS observations confirm that even when overall water quality remains acceptable, fluctuations such as unstable pH and low alkalinity can still generate measurable fish stress (Pepe-Victoriano et al., 2025).

3 Water Quality Monitoring Technologies and Data Acquisition in RAS

3.1 Conventional methods for water quality assessment

Conventional water quality assessment in RAS has relied mainly on periodic manual sampling, portable meters, and laboratory analysis of key physicochemical variables. These approaches remain foundational because they are used to track core indicators such as pH, temperature, dissolved oxygen, salinity, turbidity, and oxidation-reduction conditions, but they are labor-intensive and provide only intermittent snapshots of system status rather than continuous process awareness (Lindholm-Lehto, 2023). In intensive recirculating systems, that sampling logic is useful for routine compliance and baseline husbandry, yet it is inherently limited when water quality shifts rapidly between observation intervals.

The main weakness of conventional assessment is therefore not analytical validity but delayed detection of critical change. Manual sampling and laboratory workflows are costly in labor and time, do not support immediate intervention, and can miss off-hour excursions in dissolved oxygen, pH, or temperature that affect fish performance before personnel become aware of them (Figure 1) (Flores-Iwasaki et al., 2025). At the same time, RAS water assessment increasingly extends beyond basic field measurements to more specialized analyses, including in situ ion chromatography for continuous nitrite and nitrate monitoring and HPLSEC-fluorescence methods for tracking dissolved organic matter under oxidative treatment conditions.

3.2 Application of sensor networks and IoT technologies

Sensor networks and IoT technologies have shifted RAS monitoring from interval-based observation to real-time acquisition and remote supervision. Current systems integrate sensors for temperature, pH, dissolved oxygen, turbidity, salinity, conductivity, or water level with wireless communication modules and cloud-connected dashboards, allowing farmers to visualize conditions continuously and receive warning signals when thresholds are exceeded (Malandrakis, 2025). This architecture is especially valuable in RAS because equipment failures or rapid water-quality deterioration can escalate quickly, making immediate alerts and remote access more useful than retrospective records alone.

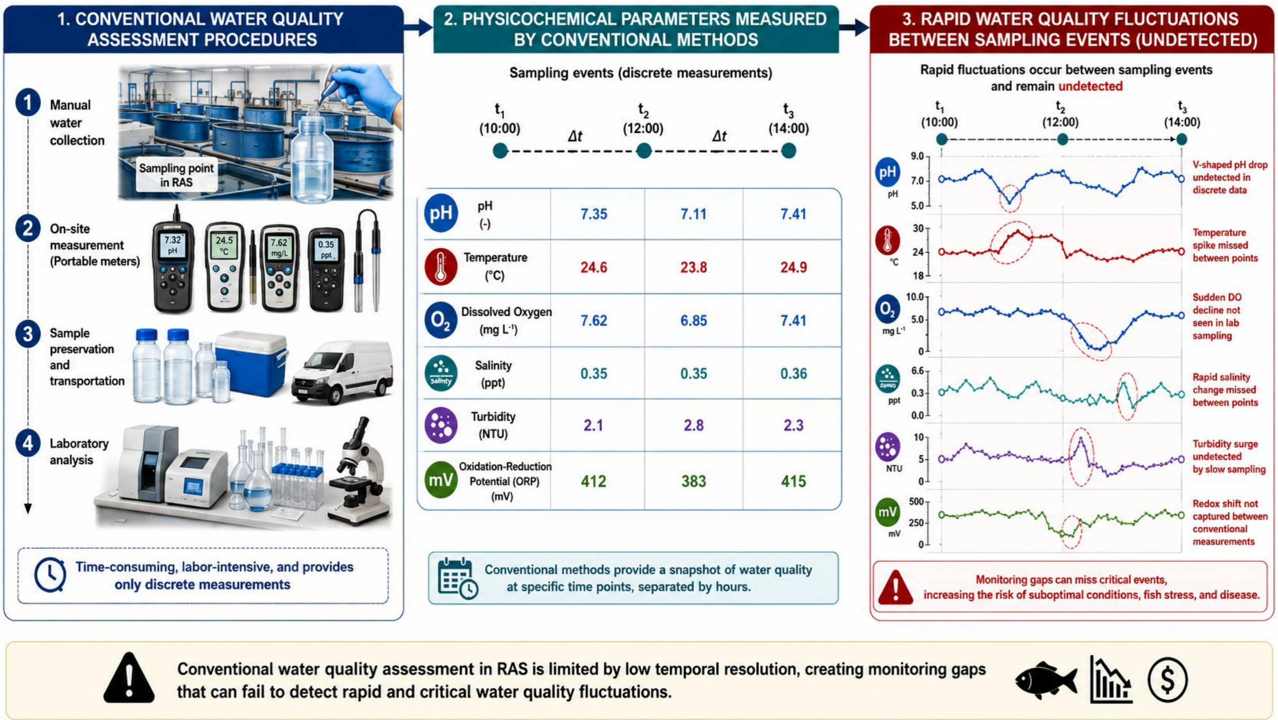

Figure 1 Conventional water quality assessment workflow and temporal limitations in recirculating aquaculture systems

Recent implementations show that IoT-enabled monitoring is becoming more accurate, more distributed, and more operationally practical across aquaculture settings. NB-IoT systems have achieved stable long-distance transmission and accurate control of temperature, dissolved oxygen, and pH, while review evidence shows that real-time monitoring remains the dominant delivered function and that temperature, dissolved oxygen, and pH are the most frequently prioritized variables in IoT-based aquaculture platforms. Even so, these systems still face practical constraints involving calibration, maintenance, automation depth, and performance in remote areas, which explains why many platforms remain focused on monitoring and alerts rather than fully autonomous control (Lindholm-Lehto, 2023; Flores-Iwasaki et al., 2025).

3.3 Data integration and feature extraction for aquaculture management

The next stage of RAS monitoring is not simply collecting more data, but integrating heterogeneous sensor streams into models that can extract useful features for management. Water quality in aquaculture is shaped by nonlinear interactions among fish density, feeding, climate, and interdependent parameters, so predictive systems increasingly use machine learning to capture temporal patterns and forecast variables such as dissolved oxygen and pH before harmful shifts occur (Baena-Navarro et al., 2025). This transition turns data acquisition into decision support by linking real-time monitoring with early warning, trend detection, and operational planning.

Feature extraction is central to this transition because raw time-series signals are often noisy, redundant, and difficult to interpret directly. Hybrid deep-learning frameworks now use convolutional layers to extract local features from timestamped water-quality data and recurrent units such as GRU or LSTM to learn sequential dependencies, while intelligent RAS analytics systems also use relational data analysis to detect sensor faults and infer relative parameter changes with lower hardware requirements (Yang et al., 2023). More broadly, machine learning in aquaculture has expanded beyond water-quality prediction alone to include biomass estimation, fish identification, and behavioral analysis, suggesting that future RAS management will depend on integrated data pipelines that combine environmental sensing with biological response indicators (Singh et al., 2024).

4 Strategies for Water Quality Control in Recirculating Aquaculture Systems

4.1 Mechanical and biological filtration technologies

Mechanical and biological filtration form the core treatment sequence in recirculating aquaculture systems because RAS water contains both suspended solids and dissolved metabolic wastes that must be removed continuously to maintain fish health. Reviews of RAS treatment equipment describe physical filtration units such as microscreen drum filters, foam fractionators, and other solid-liquid separation devices as the main tools for removing residual feed, feces, and fine suspended particles before they impair downstream treatment performance, while the broader water treatment unit is recognized as the central barrier against pollutant accumulation in the recirculating loop (Li et al., 2023). This front-end solids removal step is strategically important because particulate waste is one of the main hazardous fractions generated by feeding and fish excretion, and its early capture reduces organic loading on later biological processes.

Biological filtration then stabilizes water quality by converting toxic nitrogenous wastes into less harmful forms through microbially mediated nitrification. Biofilters are the defining feature of intensive RAS and operate through microbial consortia that oxidize ammonia to nitrate, with nitrifying bacteria growing either in suspension or as biofilms attached to fixed media; accordingly, technologies such as fluidized sand biofilters, moving-bed biofilm reactors, and rotating biological contactors are widely used because they provide the surfaces and hydrodynamic conditions needed for sustained microbial activity. Future optimization of these systems depends not only on reactor design but also on better management of microbial ecology, since biofilter success is ultimately determined by the structure and function of the biological community embedded within the filter matrix.

4.2 Oxygen management and gas exchange regulation

Oxygen management is a central water quality control strategy in RAS because high stocking density and continuous microbial oxidation create strong and variable oxygen demand. Artificial aeration remains essential for maintaining dissolved oxygen at suitable levels, and aerator selection must balance transfer performance with operating cost, while broader dissolved oxygen control research shows that keeping DO near a desired setpoint is important not only for fish health but also for treatment efficiency and energy use (Li et al., 2022). In practice, this means oxygen supply systems must be designed as control technologies rather than simple accessories, with sizing and operation matched to biomass, feed load, and the oxygen demand of biofilters.

Gas regulation in RAS also requires effective removal of carbon dioxide and, increasingly, more precise control architectures for oxygen delivery. Recent work on hybrid degassers shows that excessive CO_2 accumulation and oxygen depletion jointly reduce water quality and production efficiency, and that combined packing-media configurations can improve both CO_2 stripping and oxygenation performance; at the same time, control-system reviews indicate that although predictive, fuzzy, and hybrid DO controllers are being developed, PID-based approaches remain the most widely implemented in engineering practice (Li et al., 2022). Complementary methods such as hydrogen peroxide dosing can also contribute when carefully applied, because they can simultaneously increase oxygen saturation and reduce microbial load without measurable fish stress or biofilter impairment under appropriate conditions.

4.3 Nutrient and waste management approaches

Nutrient and waste management in RAS must address not only ammonia and nitrite toxicity but also the longer-term buildup of nitrate and other dissolved wastes. Conventional indoor RAS typically rely on solids capture followed by nitrification inside the recirculating loop, yet nitrification alone shifts waste from ammonia to nitrate rather than eliminating total nitrogen, which is why nitrogen accumulation remains a major challenge in sustainable high-reuse systems (Preena et al., 2021). This limitation becomes more important as water exchange is reduced, since system sustainability then depends on internal waste reduction rather than dilution.

For that reason, current nutrient management increasingly emphasizes denitrification, anammox, sludge digestion, and biological assimilation pathways that reduce waste mass rather than only transforming it. Denitrification can lower energy and water demand because it reduces the need for aeration and minimizes water exchange, while coupled nitrification-denitrification systems in biofilters and bioreactors can promote total nitrogen removal through the coexistence of autotrophic nitrifiers, aerobic denitrifiers, anammox organisms, and comammox populations; in parallel, plant uptake and extractive organisms can convert dissolved nutrients into useful biomass, especially in integrated treatment configurations (Preena et al., 2021). Overall, the most effective waste-management strategies are those that integrate nitrogen conversion, sludge handling, and nutrient recovery into one coordinated treatment framework rather than treating each waste stream in isolation.

5 Fish Health Management Under Recirculating Aquaculture Conditions

5.1 Effects of environmental stress on fish growth and immunity

Fish health management in RAS begins with controlling environmental stress because intensive rearing exposes fish to suboptimal water quality, crowding, and handling stressors that impair health and increase disease susceptibility. Broad aquaculture reviews show that intensive systems tend to weaken immune function and reduce performance when environmental conditions deteriorate, making stress reduction a primary requirement for sustainable production rather than a secondary welfare concern (Kari, 2025). In practice, this means that fish growth and immunity in RAS should be interpreted as direct biological responses to the rearing environment.

Experimental RAS evidence confirms that specific physical stressors can alter growth and immune status even when basic water quality is held constant. In turbot, excessive flow velocity reduced growth and antioxidant capacity while activating stress- and immune-related responses, whereas a moderate velocity improved feed intake, specific growth rate, and innate immune indicators, showing that hydraulic conditions themselves can shift fish from adaptive stimulation to chronic stress.

Stocking density is another major environmental driver of fish condition in recirculating systems because it amplifies social stress, metabolic loading, and physiological strain. In juvenile Chinese sturgeon reared in RAS, high density significantly suppressed growth, downregulated growth hormone and IGF-I signaling, and increased cortisol, glucose, lactate, and HSP70 expression, indicating a coordinated stress response linked to impaired somatic performance. The same high-density treatment also depressed antioxidant enzyme activity and reduced serum IgM, lysozyme, alkaline phosphatase, acid phosphatase, and multiple immune-related transcripts, showing that chronic crowding can weaken both oxidative defense and immune competence.

Environmental change in RAS can also produce species- and context-dependent stress responses that are not always maladaptive but still require management. During centrifugal pumping in commercial Atlantic salmon RAS, primary and secondary stress responses were triggered, yet fish maintained homeostasis over the recovery period, while in pikeperch, transfer from pond nursing to RAS dry-feed habituation elicited stronger cortisol and immunoglobulin responses in one generation that appeared to support better adaptation during that phase. These findings indicate that fish health management should distinguish between short-term adaptive responses and prolonged stress that erodes growth, immunity, and resilience.

5.2 Disease prevention and health monitoring strategies

Disease prevention in RAS is most effective when it is organized around preventive health management rather than treatment after outbreaks occur. Epidemiological reviews conclude that no single measure is sufficient and that successful disease control requires a combination of surveillance, biosecurity, immunoprophylaxis, and legally approved therapeutics, while aquaculture management reviews similarly emphasize strict biosecurity as essential as fish movements and intensification raise the risk of pathogen introduction and economic loss. This preventive logic is especially important in recirculating systems because their closed design can allow pathogens to persist once introduced.

Modern RAS health monitoring is therefore shifting toward continuous, non-lethal, and system-level detection methods. Recent salmon work showed that eDNA/eRNA from RAS water can track pathogen dynamics non-invasively and provided strong correlations between water samples and gill swabs for SGPV and ISAV-HPR0, demonstrating that water itself can function as an early diagnostic matrix in recirculating systems. In parallel, IoT-based monitoring frameworks are being developed to combine real-time sensor data, machine learning, and remote alerts so that water quality deterioration and pathogen indicators can be recognized before disease becomes clinically obvious.

Health monitoring in RAS also needs to include organ-specific and colony-level surveillance because water quality effects do not always present as overt mortality. Gill-focused reviews show that RAS conditions can affect gill health, but current findings are inconsistent partly because many studies inadequately report water quality; they therefore recommend more holistic assessment using histology, pathogen screening, gene expression, and microbiome analysis (Bjørgen et al., 2024). Facility-level programs in recirculating systems likewise emphasize monitoring both individual and population health and preventing pathogen entry and spread through structured biosecurity protocols that can be adapted across facility sizes.

An important emerging opportunity is to use controlled environmental manipulation as part of preventive health management, while recognizing its risks. In a commercial RAS nursery, short-term non-lethal heat shock induced heat shock proteins and appeared to protect fish from opportunistic infection, suggesting that managed environmental-microbial-host interactions can support disease control; however, excessive temperature stress also risked microbiota dysbiosis and mortality, so such approaches require precise control and monitoring (Ng et al., 2024).

5.3 Integration of nutrition and environmental management

Nutrition and environmental management are tightly linked in RAS because dietary adequacy partly determines how fish tolerate water-quality and husbandry stress. Reviews of stress management in aquaculture show that dietary interventions can improve immunocompetence and stress resistance when environmental challenges are unavoidable, and more recent synthesis argues that nutritional immunomodulation is an effective non-pharmaceutical strategy for improving resilience to both pathogens and environmental stressors (Kari, 2025). This makes feeding strategy a central part of fish health management rather than a separate production variable.

The strongest mechanistic evidence points to the roles of vitamins, minerals, amino acids, and other functional feed components in supporting mucosal integrity, antioxidant defense, cytokine activity, and immune cell growth under stress. Earlier reviews found that diets fortified above minimum requirement with selected nutrients, probiotics, prebiotics, and immunostimulants can improve disease resistance, stress tolerance, and reduce reliance on antibiotics, while intestine-focused work emphasizes that balanced diets protect gut barriers and thereby support whole-body immunity. In RAS, where environmental fluctuations can quickly disrupt feeding and microbial balance, these nutritional effects are particularly relevant to maintaining stable health.

Integration also extends to developmental strategy, because nutritional programming can shape later stress tolerance and feed utilization. Early-life dietary interventions have been linked to persistent changes in nutrient use, digestive enzyme activity, and immune responses, and recent reviews argue that species-specific, development-stage-targeted immunonutrition represents a major advance for precision aquaculture (Kari, 2025). This suggests that health management in RAS should begin before grow-out, with feeding protocols designed to prepare fish for intensive recirculating conditions.

At the system level, integrating nutrition with environmental control aligns fish health goals with broader sustainability goals. Dynamic RAS models show that management decisions can be linked to predicted fish growth and mortality under different environmental conditions, while nutrition-sensitive aquaculture frameworks argue that production systems should optimize animal performance and health without compromising environmental sustainability and human wellbeing (Kamali et al., 2022). Overall, effective fish health management in RAS depends on coordinated control of rearing conditions, preventive monitoring, and precision nutrition rather than on any single intervention alone.

6 Case Study: Integrated Water Quality Control and Fish Health Management in a Commercial RAS Facility

6.1 System design and monitoring framework

A commercial RAS case study is best framed as a multi-unit control system in which tank performance depends on both water treatment design and continuous monitoring. Field and facility evaluations show that practical RAS layouts combine fish tanks with dedicated treatment and purification units, and that clear description of water process flow, treatment components, and species-specific water quality limits is essential for benchmarking performance and refining future commercial designs. This design logic matters because effective facility evaluation requires not only acceptable production outcomes but also explicit performance standards for water quality and system function across operating conditions (Mota et al., 2022).

Within that framework, the monitoring system in a commercial RAS must follow the variables most tightly linked to fish stress and operational failure. Reviews and commercial-scale monitoring studies agree that temperature, pH, dissolved oxygen, and related nitrogen compounds must be kept within narrow ranges, while recent kingfish data show that CO_2, pH, temperature, nitrogen compounds, and hydrogen sulfide can be maintained within published safety thresholds when monitoring is systematic and sustained. The same evidence base also shows that monitoring is moving from periodic handheld testing toward automated, real-time acquisition, because conventional lagged measurements are poorly suited to intensive systems where pump or aerator failure can trigger rapid oxygen depletion and water quality deterioration (Figure 2) (Lindholm-Lehto, 2023; Malandrakis, 2025).

6.2 Analysis of water quality variation and fish performance responses

Commercial and near-commercial RAS studies show that water quality variation is not biologically neutral, because shifts along the treatment train and over time translate into measurable differences in fish performance. In an integrated land-based RAS, water quality changed gradually along the direction of flow, and fish production responded to those differences through variation in final weight, survival, specific growth rate, and yield. Correlation analysis in that system further showed that the main cultured species performed better under mesotrophic or oligotrophic conditions, indicating that performance responses depend on how well local water conditions match species-specific tolerances.

Temporal variability inside RAS is also uneven across parameter classes, which has direct implications for fish health interpretation and management. In Atlantic salmon research facilities, sensor-controlled parameters showed relatively low variation, whereas parameters dependent on biofilter maturation and performance varied much more strongly, and variation among experimental trials exceeded variation within trials (Mota et al., 2022). Complementary dynamic modeling indicates that growth and mortality relationships can be used to predict fish well-being under changing environmental conditions and management strategies, supporting the use of water-quality variation as a leading indicator of both welfare risk and production efficiency (Kamali et al., 2022).

6.3 Development of intelligent management strategies

The next step in a commercial RAS case study is to convert monitoring into intelligent management, where sensor data drive adaptive interventions rather than passive record-keeping. Commercial-scale control research shows that reinforcement-learning architectures can combine feeding optimization with water quality management, using modular design, robust sensor networks, and fault-tolerant control to maintain fish growth and stable environmental conditions across large facilities. Performance gains from this approach are substantial, with reported improvements including 15.5% better feed conversion, 96.8% water-quality maintenance, and 31.5% lower operational cost, indicating that integrated control can improve both biology and economics (Elmessery et al., 2025).

Intelligent management also increasingly includes automated interventions, predictive analytics, and behavior-linked control. IoT-ML systems have supported more than 6000 corrective interventions, including automated oxygenation and pH adjustment, while maintaining survival above 90% under challenging seasonal conditions, and deep learning-based aeration control has reduced energy use while accelerating growth under stable water quality conditions (Baena-Navarro et al., 2025). Even so, the literature remains cautious: AI-assisted imaging, behavior monitoring, and predictive tools are advancing quickly, but some reviews note that many machine-learning systems are still validated mainly in smaller tanks rather than fully commercial RAS scales (Gupta et al., 2024).

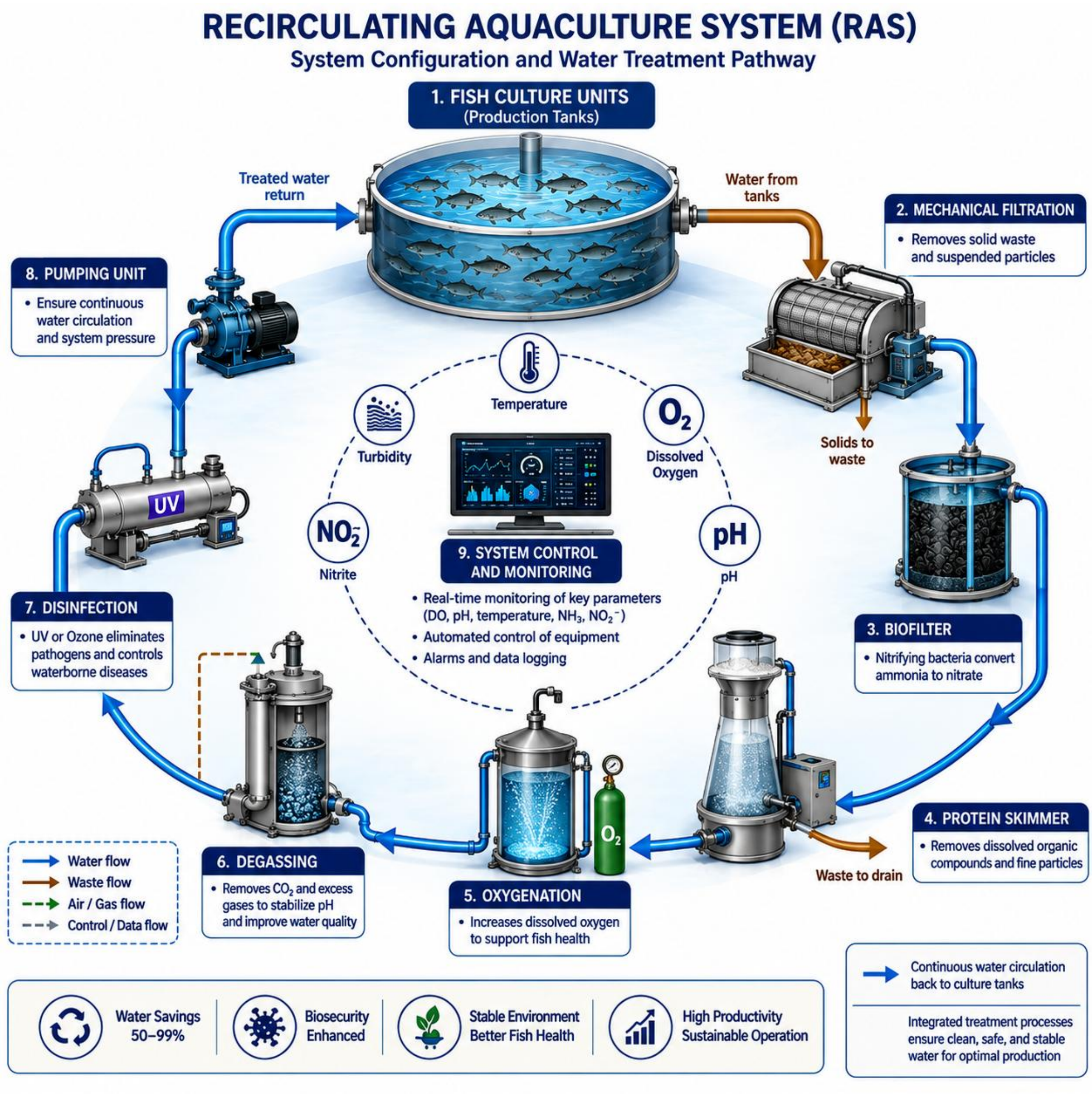

Figure 2 Structural configuration and water treatment pathway of a commercial recirculating aquaculture system

7 Intelligent Technologies and Future Development of RAS Management

7.1 Artificial intelligence and predictive modeling for aquaculture management

Artificial intelligence is becoming a core tool in RAS management because water quality control increasingly depends on predicting system change before biological stress or equipment failure occurs. Recent RAS-focused work argues that future water status must be forecast in advance to support control strategy generation in multi-unit systems, while broader AIoT reviews show that predictive models such as LSTM and related methods are already being used to monitor dissolved oxygen, pH, and temperature for real-time intervention (Yang et al., 2023). This shift matters because predictive management turns monitoring from passive observation into active decision support, allowing farmers to anticipate instability rather than merely respond to it after thresholds are crossed (Huang and Khabusi, 2025).

Current predictive models in aquaculture are increasingly designed to reduce redundant inputs and extract the most informative features from complex time-series data. Hybrid deep-learning frameworks for RAS combine convolutional layers, recurrent units, and attention mechanisms so that local patterns, sequential dynamics, and critical features can be learned together, while feature-selection work in outdoor recirculation systems shows that a small subset of routinely measured variables can effectively support prediction of dissolved oxygen, TAN, nitrite, and alkalinity (Jongjaraunsuk et al., 2024). Even so, predictive performance remains parameter-specific, since the same outdoor study found strong prediction for several variables but substantially weaker performance for pH, indicating that model reliability still depends on the biological and chemical behavior of the target parameter (Yang et al., 2023).

AI is also expanding beyond water chemistry prediction into growth modeling and operational optimization. In a smart aquaculture management system, deep learning linked environmental and system parameters to California bass growth with high predictive accuracy, and the resulting model was proposed for integration into autonomous feeding to reduce leftover feed. More generally, systematic reviews conclude that AI now supports decision-making, optimization, and automation across feeding, disease monitoring, production modeling, and environmental management, suggesting that future RAS platforms will increasingly connect fish performance prediction with water-quality control in a single analytical framework (Aung et al., 2024).

AI-based analytics are also being adapted for practical use in lower-cost and resource-constrained environments rather than only in highly capitalized farms. IoT-linked analytics systems have identified strong correlations among water variables, including substantial associations of pH with dissolved oxygen and temperature, which can guide simpler predictive control rules, while other smart aquaculture systems report that Random Forest models can outperform alternative algorithms for classification-based water-quality prediction tasks (Matkarimov et al., 2025). This suggests that the future of predictive RAS management will likely include both advanced deep-learning architectures for large datasets and lighter-weight models that are easier to deploy where infrastructure, computing capacity, or technical expertise are limited.

7.2 Automation and smart control systems in RAS

Automation in RAS is moving from isolated sensors toward connected systems that both detect change and trigger corrective action. Recent reviews note that many farms still rely on manual measurements or disconnected devices despite the availability of real-time sensing, while cost-effective RAS platforms now outline the transition from passive monitoring to closed-loop control through continuous feedback, error calculation, and actuator commands (Grandez-Yoplac et al., 2025). In this architecture, smart control depends on linking sensors, communication networks, cloud or edge processing, and actuators into a single operational loop rather than treating monitoring and intervention as separate tasks (Malandrakis, 2025).

Prototype and commercial-oriented systems already show how this logic can be implemented in practice. RAS automation platforms based on Raspberry Pi, cloud connectivity, and modular sensor networks have been designed to support real-time acquisition, intelligent aeration, and visualization, while a tilapia RAS prototype automatically monitored and controlled pH, temperature, salinity, and dissolved oxygen with measurements accessible through a web application (Libao et al., 2024). These systems indicate that smart RAS control is no longer limited to theory, because they connect environmental sensing directly to user interfaces and operational responses that can be accessed remotely (Shodiq et al., 2023).

A central benefit of automation is that it reduces the biological risk created by delayed human response. Recent IoT monitoring reviews report that sensor-based water monitoring improves growth, reduces mortality, and enables rapid prediction and detection of atypical TAN levels, while integrated IoT-ML systems have carried out thousands of corrective interventions and maintained fish survival above 90% under demanding conditions (Baena-Navarro et al., 2025; Flores-Iwasaki et al., 2025). This matters particularly in RAS because pumps and aerators are life-support components, and automation can shorten the time between deviation detection and intervention when oxygen depletion or ammonia accumulation develops rapidly (Malandrakis, 2025).

Automation is also broadening from water-quality regulation to behavior-linked and vision-based management. Reviews of recent RAS developments describe AIoT systems that reduce manpower and machine-vision tools that detect altered swimming behavior as an early warning of suboptimal water conditions, including hydrogen sulfide exposure below the known toxicity threshold (Gupta et al., 2024). Together with smart feeding systems that improve feed conversion and growth while reducing waste, these tools indicate that the next phase of RAS automation will combine environmental control with behavioral sensing and production optimization rather than focusing on physicochemical variables alone (Huang and Khabusi, 2025).

7.3 Challenges and future perspectives

The main barriers to intelligent RAS adoption remain economic, technical, and organizational rather than conceptual. Recent reviews describe high installation cost, connectivity problems in rural areas, and demanding calibration and maintenance requirements as major obstacles to smart RAS implementation, while earlier industry analysis identified poor system design and weak management capacity, especially the shortage of skilled personnel responsible for water quality and mechanical issues, as persistent constraints on RAS performance. These barriers explain why intelligent technologies have advanced faster in research and prototypes than in broad commercial uptake (Grandez-Yoplac et al., 2025).

A second major challenge is scale, robustness, and data quality. AI and IoT reviews emphasize that widespread deployment is still limited by restricted access to representative datasets, expensive sensor and AI infrastructure, and technical complexity, while water-quality management reviews further note persistent issues with sensor biofouling, recalibration, and performance across diverse environments (Aung et al., 2024). The future direction is therefore not simply more algorithm development, but more transferable systems that are resilient under real farm variability and that can operate reliably with local maintenance capacity (Huang and Khabusi, 2025).

Energy use and sustainability will also shape the future of intelligent RAS management. Although RAS are highly water-efficient and relatively insulated from climate variability, energy consumption and greenhouse gas emissions remain major limiting factors, and broader systems analyses argue that renewable energy integration combined with advanced monitoring and process optimization could improve both environmental and economic feasibility. Future intelligent RAS will therefore likely be judged not only by how well they stabilize water quality and fish health, but also by how effectively they reduce energy demand through system-wide optimization (Ahmed and Turchini, 2021).

The strongest near-term development pathway combines better sensing, tighter automation, and broader biological data integration. Proposed priorities include self-calibrating multi-parameter sensors, low-power communication technologies such as LoRaWAN and NB-IoT, and expansion of monitored variables to include microbiological and emerging-contaminant indicators, all of which would support more comprehensive and autonomous environmental control (Baena-Navarro et al., 2025). More broadly, recent RAS reviews describe a thematic shift from classical engineering variables toward proteomics, transcriptomics, and molecular techniques, suggesting that future intelligent management will increasingly fuse environmental monitoring with microbial and genomic evidence for disease control, growth optimization, and precision aquaculture (Grandez-Yoplac et al., 2025).

8 Conclusions

Recent advances in water quality control technologies for RAS show a clear transition from conventional treatment and intermittent measurement toward integrated, real-time, and more intelligent control systems. Current RAS performance depends on coordinated use of mechanical and biological filtration, gas regulation, disinfection, and monitoring tools that remove suspended solids, nitrogenous wastes, carbon dioxide, and other hazardous compounds while maintaining conditions suitable for fish growth. At the same time, modern monitoring has expanded from labor-intensive handheld sampling to sensor-based surveillance, IoT connectivity, and AI-assisted warning systems that improve the speed and precision of operational responses.

Technological progress is also moving beyond basic recirculation toward process intensification and adaptive optimization. Dynamic and reinforcement-learning models now link feeding, oxygenation, biofilter behavior, and water chemistry, allowing managers to anticipate parameter changes and maintain higher water-quality stability under changing operational loads. In parallel, targeted treatment innovations such as side-loop denitrification, sand filtration, and advanced oxidation have improved nutrient removal and water reuse, although some promising methods still require caution because water-quality gains can be accompanied by emerging risks such as instability over time or increased antibiotic resistance genes.

The literature consistently shows that water quality management and fish health protection are inseparable in RAS. Fish health in recirculating systems is directly shaped by the quality of the production water, while the accumulation of ammonia, nitrite, carbon dioxide, organic matter, and other hazardous compounds can compromise growth, welfare, and survival if treatment performance declines. This linkage is especially important because opportunistic pathogens remain difficult to manage in RAS, and some conventional chemotherapeutic approaches can themselves disrupt biofilters and further destabilize water quality.

An integrated health-protection strategy therefore requires not only good engineering control, but also biological surveillance and multi-level assessment. Changes in water quality are reflected in fish behavior and can support early detection of stress, while more comprehensive health monitoring increasingly includes histology, pathogen screening, gene expression, and microbiome-based assessment of gill condition and mucosal health. Across the broader RAS literature, this integration is now reinforced by digital tools that connect environmental monitoring with predictive modeling, welfare indicators, and management decisions aimed at sustaining both fish performance and biosecurity.

Future opportunities for sustainable recirculating aquaculture lie in combining digitalization, circular resource use, and lower-impact system design. RAS already offers major sustainability advantages through reduced water use, improved waste management, nutrient recycling, and reduced exposure to climate variability, but wider adoption still depends on making systems more energy-efficient, more affordable, and easier to manage at commercial scale. The next generation of sustainable RAS will likely depend on better integration of smart sensing, autonomous control, and predictive models that reduce risk while improving resource efficiency and operational consistency.

A second major opportunity is to close the RAS loop more completely by recovering value from waste streams rather than treating them only as disposal problems. Integrated farming approaches, including aquaponics, wetlands, algal systems, and microalgae-based nutrient recovery, can recycle nitrogen and phosphorus, generate useful co-products, and improve the environmental and economic performance of land-based fish production. Overall, the future of RAS will depend on how effectively the sector combines advanced water-quality control, fish-health-centered management, and circular bioeconomy strategies to produce seafood with lower environmental cost and greater long-term resilience.

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