

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).