

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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