

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-