

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.