

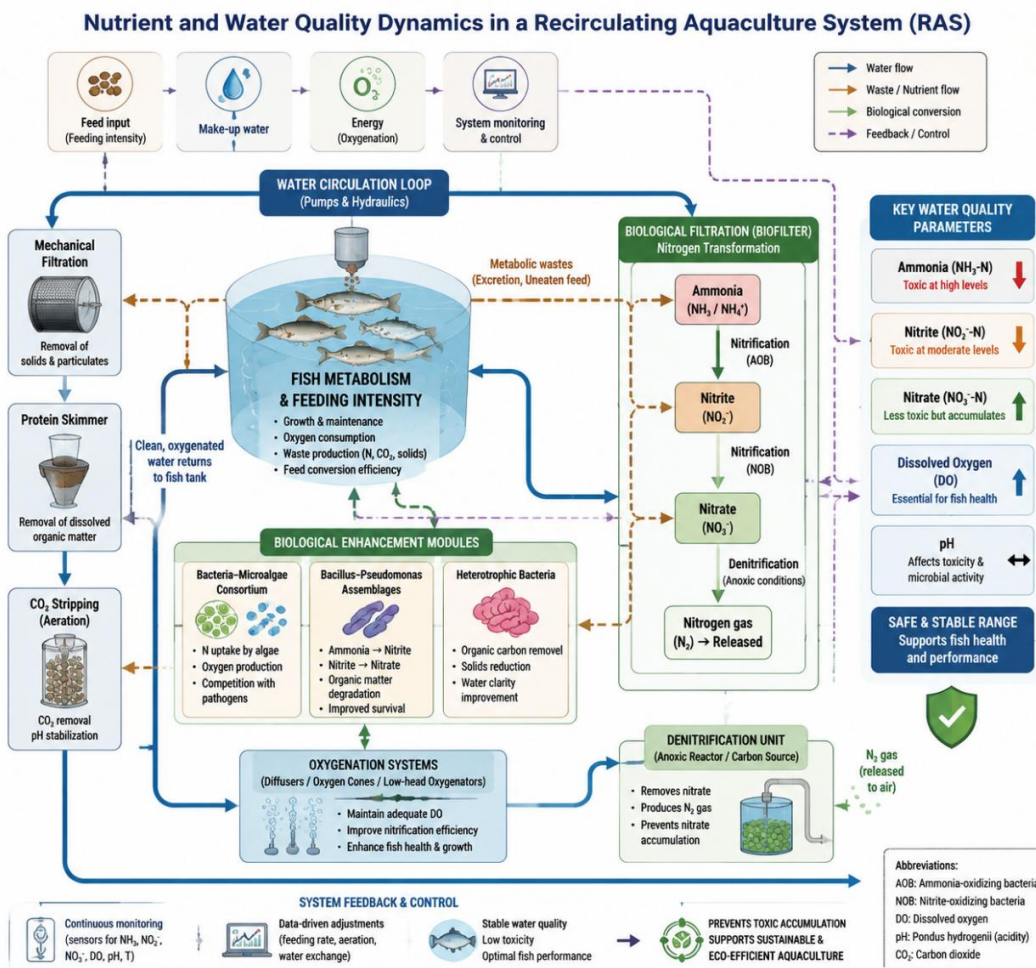


Figure 2 Systems-level interactions in recirculating aquaculture systems (RAS), illustrating feedback loops between fish metabolism, nitrogen cycling processes, and biological treatment units including nitrifying bacteria, bacterial consortia, and microalgae

Balancing protein with non-protein energy is critical to spare protein for growth and limit catabolic stress under high temperature. In large yellow croaker, elevating dietary lipid from 60 to 90 g/kg improves weight gain and nitrogen retention, but further increase to 120 g/kg does not enhance performance, implying an upper threshold for effective energy supplementation (Chen et al., 2023). The same study estimates a suitable dietary energy content around 19 MJ/kg and notes that when energy needs are satisfied, additional lipid no longer induces protein-sparing, which is important when setting rations during hot seasons.

6.2 Functional feed additives

Under high-temperature, high-density culture, functional additives that stabilize immunity and gut health become key complements to macronutrient adjustments. Broad aquaculture evidence shows that bio-friendly supplements such as probiotics, prebiotics and synbiotics can improve growth and stress mitigation while modulating intestinal microbiota and immune competence, thereby reducing reliance on antibiotics. Reviews on aquaculture feed additives further emphasize that immunostimulants (e.g., β -glucans, nucleotides) and prebiotics regulate innate defenses and gut barrier function, with typical inclusion ranges of a few g/kg diet (Okon et al., 2025).

For large yellow croaker specifically under summer heat stress, dietary inulin has emerged as a promising prebiotic strategy. A two-month trial across July-September showed that an inulin level around 0.4% significantly improved growth, accompanied by up-regulation of glycolysis and fatty-acid biosynthesis genes and increased metabolites supporting energy production. Inulin also reshaped the gut microbiota with enrichment of beneficial bacteria such as *Lactobacillus* and higher levels of short-chain fatty acids and amino acids, suggesting enhanced nutrient absorption and thermal stress tolerance (Yin et al., 2026).