

ammonium nitrogen and nitrite accumulation (Zhang et al., 2024). Enzyme activity in sediments and coupled nitrogen-phosphorus cycling can regenerate large amounts of dissolved inorganic nutrients; if these nutrients cannot be effectively absorbed and utilized by biota, they will further aggravate water eutrophication and aquaculture disease risks (Bai et al., 2022). Therefore, one of the core functions of ecological food chain closure is to reincorporate these potentially polluting nutrients into the internal cycling of the pond-farm system, transforming them from "wastes" into reusable ecological resources.

Ecological food chain closure realizes nutrient cycling through the multi-stage process of "microbial decomposition-plant uptake-animal reuse." Microbial communities first decompose residual feed, feces, and organic detritus, converting complex organic matter into inorganic nutrients such as ammonia nitrogen and phosphate. Phytoplankton, aquatic plants, and artificial floating-bed plants further absorb nitrogen, phosphorus, and other nutrients in the water, thereby reducing the risk of eutrophication. Zooplankton, filter-feeding fish, shellfish, and benthic animals can then utilize algae, suspended particles, and deposited organic matter, converting low-level resources into harvestable biomass. Model analyses and budget assessments show that macrophytes and other primary producers can contribute more than half of nitrogen and phosphorus retention, indicating that plant and microbial components play key roles in closed nutrient cycling (Campanati et al., 2021; Zhang et al., 2024).

Ecological engineering and integrated multi-trophic aquaculture (IMTA) further restructure nutrient cycling pathways, allowing feed residues and excreta to be gradually transformed and absorbed by multiple biological sinks. For example, in freshwater IMTA-aquaponic systems, fed fish convert part of dietary nitrogen and phosphorus into biomass, detritivores and filter feeders recover nutrients from particulate matter, and macrophytes and hydroponic vegetables assimilate dissolved nutrients, increasing overall nitrogen and phosphorus utilization efficiency to more than 80%~90% and significantly reducing discharge (Figure 2) (Campanati et al., 2021; Goda et al., 2024). Microalgae-bacteria consortia, biofilms, and functional microbial groups involved in nitrification, denitrification, and organic phosphorus hydrolysis are important foundations supporting this cycling process. They can transform toxic forms of nitrogen into biomass or inert end products while providing material support for organisms at higher trophic levels (Biswas et al., 2020).

3.2 Water self-purification and ecological regulation mechanism

Ecological food chain closure can enhance the water self-purification capacity of freshwater ponds. The key lies in the coordinated configuration of hydraulic processes, habitat structures, and biological components, which enables pollutants to be intercepted, settled, absorbed, and transformed along the water flow pathway. Aquatic plants absorb nutrients such as nitrogen and phosphorus through their roots, stems, leaves, and associated microorganisms, while also providing attachment substrates and habitats for microorganisms and small aquatic animals, thereby helping stabilize the ecological structure of the water body. Phytoplankton can release oxygen through photosynthesis, but excessive proliferation may cause algal blooms and diel fluctuations in dissolved oxygen; therefore, filter-feeding fish, shellfish, and zooplankton are needed for moderate regulation to maintain algal abundance within a relatively reasonable range. Cascade pond systems, ecological engineering pond aquaculture systems, and recirculating pond systems equipped with ecological ponds usually employ sequential structures such as ditches, settling units, vegetated zones, biofilm-rich purification ponds, and culture ponds to progressively remove ammonia nitrogen, total nitrogen, total phosphorus, organic matter, and phytoplankton (Liu et al., 2014). Relevant measurements show that the removal rates of total nitrogen and total phosphorus in such systems often exceed 40%~60%, and chlorophyll a and chemical oxygen demand are also significantly reduced, allowing culture ponds to maintain lower nutrient and algal levels than conventional ponds under similar or even higher production conditions (Biswas et al., 2020).

Microorganisms play a fundamental role in water purification and ecological regulation. Beneficial microbial communities can promote organic matter degradation, participate in nitrification, denitrification, and sediment remediation, and reduce the accumulation of harmful substances such as ammonia nitrogen, nitrite, and hydrogen sulfide. High-throughput sequencing studies have shown that Proteobacteria, Actinobacteria, Bacteroidetes,