

polyculture systems, demonstrating the advantages of multi-trophic complementarity. From an economic perspective, combinations of shrimp, filter-feeding animals, and macroalgae can increase biomass yield and the survival rate of high-value shrimp, while reducing disease and stress through bioremediation, shading, and water quality stabilization, thereby improving overall returns (Thomas et al., 2020). Studies on shrimp IMTA in China have also emphasized that combinations such as shrimp + crab + clam + fish or shrimp + jellyfish + clam can be flexibly adjusted according to local species and resource conditions, making full use of pond carrying capacity and reducing tailwater discharge with little additional feed and labor input (Chang et al., 2020).

4.2 Fish-aquatic plant-microorganism ecological regulation model

The fish-aquatic plant-microorganism ecological regulation model emphasizes the synergistic effects among cultured fish, aquatic plants, and microbial communities to improve pond water quality and sediment conditions, control eutrophication risks, and enhance system self-purification capacity. Aquatic plants include submerged plants, emergent plants, floating-leaved plants, and plants on artificial ecological floating beds. They can absorb nutrients such as nitrogen and phosphorus from the water and reduce eutrophication pressure. Meanwhile, plant roots and surfaces provide substrates for microbial attachment, growth, and reproduction, forming rhizosphere microecosystems that enhance organic matter degradation and nutrient transformation. For fish culture, appropriate aquatic plant configuration can also provide shelter, buffer changes in water temperature, and improve the habitat environment of cultured animals. Taking largemouth bass ponds planted with the submerged macrophyte *Elodea nuttallii* as an example, studies have shown that integrating submerged plants into pond systems can significantly reduce total nitrogen, total phosphorus, and chemical oxygen demand, increase dissolved oxygen levels, and effectively prevent cyanobacterial blooms compared with conventional ponds without vegetation (Nie et al., 2023). Lotus-fish co-culture systems can also reduce nitrogen, phosphorus, nitrite, and COD in the water, as well as organic matter and total nitrogen in sediments, while supporting functionally beneficial archaeal and fungal networks that promote ammonia oxidation, organic matter decomposition, and pathogen suppression.

Microorganisms are an important link connecting aquaculture production and ecological purification in this model. Beneficial microbial communities in ponds can decompose residual feed, feces, and dead algae, promote the transformation of organic matter into inorganic nutrients, and participate in the transformation of substances such as ammonia nitrogen and nitrite. Aquatic plants absorb these transformed nutrients and reduce their accumulation in the water, while microorganisms in the plant rhizosphere can further improve pollutant degradation efficiency. Studies on pond microbiology have pointed out that algae and bacteria play central roles in maintaining pond productivity, regenerating nutrients, and influencing tailwater, and that management of microbial food webs is an important basis for optimizing pond production (Moriarty, 1997).

Recent studies have shown that, in recirculating ponds enhanced by bacteria-microalgae associations, targeted bioaugmentation using biofilm carriers can significantly reduce total nitrogen, ammonia nitrogen, and nitrite by altering nitrogen-cycling functional genes and microbial community composition, while increasing fish production by more than 13%. Studies on microbial and water quality dynamics in tilapia ponds have also shown that bacterial and microalgal communities are closely related to water quality parameters such as water temperature, dissolved oxygen, ammonia nitrogen, and nitrate, indicating that ecological regulation based on microbial processes is an important pathway for maintaining stable pond operation. Through the operational process of "nutrient load generated by fish culture-microbial decomposition and transformation-aquatic plant uptake and fixation-water quality improvement," this model can enhance the self-purification capacity and ecological stability of pond systems while maintaining aquaculture output (Nie et al., 2023).

4.3 Pond-ecological ditch-constructed wetland recycling purification model

The pond-ecological ditch-constructed wetland recycling purification model is an engineered closed-loop model that integrates pond aquaculture systems with external ecological purification facilities. It is particularly suitable for large-scale and contiguous freshwater pond aquaculture areas. By connecting aquaculture ponds with